A MULTILAYER AQUIFER MODEL OF THE OGALLALA FORMATION IN OKLAHOMA

By

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CHAPTER I

INTRODUCTION

Extensive utilization of groundwater systems which have low annual recharge rates has the same effect as the mining of an unreplenishable resource. The problems associated with the mining of groundwater are reflected in the social, economic, and legal framework of the area involved. In order to make the best use of groundwater systems, computer management models have been developed.

Any proposed method of management of a groundwater system must have as one of its components an accurate description of the hydrogeologic properties of the aquifer involved and their hydraulic relationships. The movements of groundwater and the responses of water levels to the development of an aquifer have been described by numerous empirical equations. The properties used in evaluating the responses of an aquifer are its coefficients of permeability, transmissibility, and storage, and its specific yield, and boundary conditions with respect to leakage and recharge. The areal extent, saturated thickness, and any anomilies must also be considered. Making predictions or estimates of the responses of an aquifer are difficult because the cause and effect relations of its properties are complex. Often there is not enough detailed information concerning the properties and their relations to give a precise definition of the aquifer. This has led to the use of investigative computer models based on applications of hydrogeologic principles with interpretation and extrapolation of the existing data.

Once the hydrogeologic properties of an aquifer are determined, they are programmed into a computer model describing the responses of the aquifer to withdrawal of water from the system. This model is then used to reproduce past responses of the aquifer and to predict future responses. The ability of the model to reproduce the past responses is used as a measure of the model's validity. In most cases there is not enough data concerning the history of an aquifer to prove unquestionably the validity of the model. Therefore, methods for determination of an aquifer's properties must continuously be refined. The relationships of these properties must also be redefined in order to more logically represent the aquifer being modeled.

The Ogallala Formation is an example of an extensively over-developed aquifer with a low annual recharge. Current water levels in some areas are lowered to such a degree as to make the aquifer unusable. Because the economy of the area depends upon water from the aquifer for irrigation, research into computer models predicting future water levels in the areas effected has been stimulated. Most investigators have considered the Ogallala as an homogenious unit, i.e., no variation in the properties of the aquifer with depth or areal extent. However, it has been shown by Frye (1970), Keys and Brown (1970), and Peral (1970) that the aquifer is discontinuously layered. Thus the question of the validity of an homogeneous approach in the modeling of the Ogallala has been proposed by research at Oklahoma State University.

The need to consider layering in a computer modeling of the Ogallala has been emphasized by recent studies. A mathematical management model for a portion of the Ogallala Formation in the Texas panhandle was developed at Texas Tech. University. This model, refined and described by Sechrist, Clayborn, Rayner and Wells (1970), considered the Ogallala to be vertically and horizontally homogeneous. Lamirand (1970) tested the Texas Tech. model with respect to its sensitivity to variation in pump rates, storage coefficient and permeability. He found the program to be insensitive to changes in permeability but sensitive to changes in the storage coefficient. The researchers at Texas Tech. had assumed an average storage coefficient for the aquifer which they obtained by averaging the coefficients of all layers involved. Because the model was sensitive to changes in the coefficient of storage, a study was undertaken to determine the effects of changing this parameter with depth in the model. DeVries and Kent (1972) refined the Texas model and introduced vertical variation of specific yield and permeability. Weighted average values for these two parameters were assumed to be representative for each layer. The results of this study showed a significant difference in the residual water levels obtained with the multi-layered approach when compared with those from the homogeneous approach. However, a need for empirical proof of the values used in the weighted average approach was evident.

Model studies make the observation of ground water phenomena a laboratory function, and as such they are very useful when direct field investigations are not possible. Four general types of physical models have been previously used to verify assumptions made about a ground water flow. These are sand, viscous fluid, electrical and membrane type models. An example of the fluid analog model is described by Steinberg and Scott

(1964). This Hele-Shaw model was used by DeWiest (1966) in investigations into the nature of multi-aquifer systems. Some sand models have been described by Todd (1960) and Lehr (1963). A sand model is an accurate representation of aquifer conditions because in both cases the liquid flow takes place through a porous media. This type model is often used in the study of flow into and around wells and well systems. DeVries and Kent (1972) decided a sand model would be the best approach for an investigation into the multilayered aquifer condition.

It is the purpose of this paper to describe the development and testing of a laboratory sand model simulating the layering conditions present in a portion of the Ogallala Formation. It was the objective of this study to obtain better estimates of the hydrogeologic properties of the formation in lieu of field pump test data which has not been available, and to define the permeability coefficient and storage fraction for each individual layer.

CHAPTER II

MATERIALS AND METHODS

Materials

Models

There were two models constructed using the same basic design (see Figure 1) and materials. The model consisted of two plastic drumlike tanks placed one inside of the other. This created an annular space as shown in Figure 1. The inner tank's wall was perforated by numerous, randomly spaced 1/4 inch diameter holes for its entire length and circumference. The sands were placed in the tank in four layers (A, B, C, D), graded finest to coarsest from top to bottom. Strips of insulation type fibre glass were used to prevent the sand from leaking out the holes in the inner tank wall. The annular space was used to regulate the level of water in the model. In order to accomplish this, there were five 1/4 inch diameter openings in the outer tank wall. These openings were positioned opposite the interface between layers, and one at the top and bottom as shown in Figure 1. The pump well was placed in the center of the inner tank of both models. In model number one there was one observation well placed at 15.24 cm from the pump well. In the second model there were four observation wells placed symmetrically on a diameter extended through the pump well.

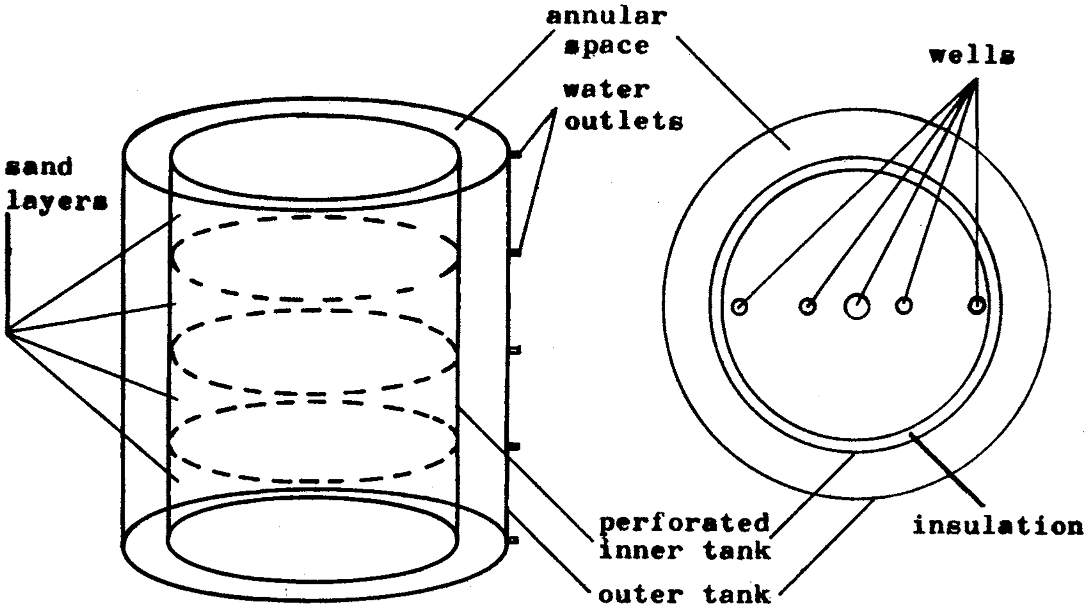


Figure 1. Basic Plan[1]

[1] Not to scale.

The pump well in both models consisted of four sections of Johnson well screen threaded together (see Figure 2). The sections were each 29.21 cm in length, and 3.165 cm in outer diameter. The effective opening of each section was chosen such that it would be appropriate for the layer it penetrated. The sections opposite A, B, C, and D were numbers 19, 20, 21, and 23, respectively. The numbers are the effective slot openings of the section in microns. The water was pumped from the model through a 1/4 inch o.d. copper tube placed inside the screen.

The observation wells were of two types (see Figure 2). One observation well was constructed from a length of 1.4 cm o.d. pipe attached to a section of No. 21 Johnson well screen with a sand point on

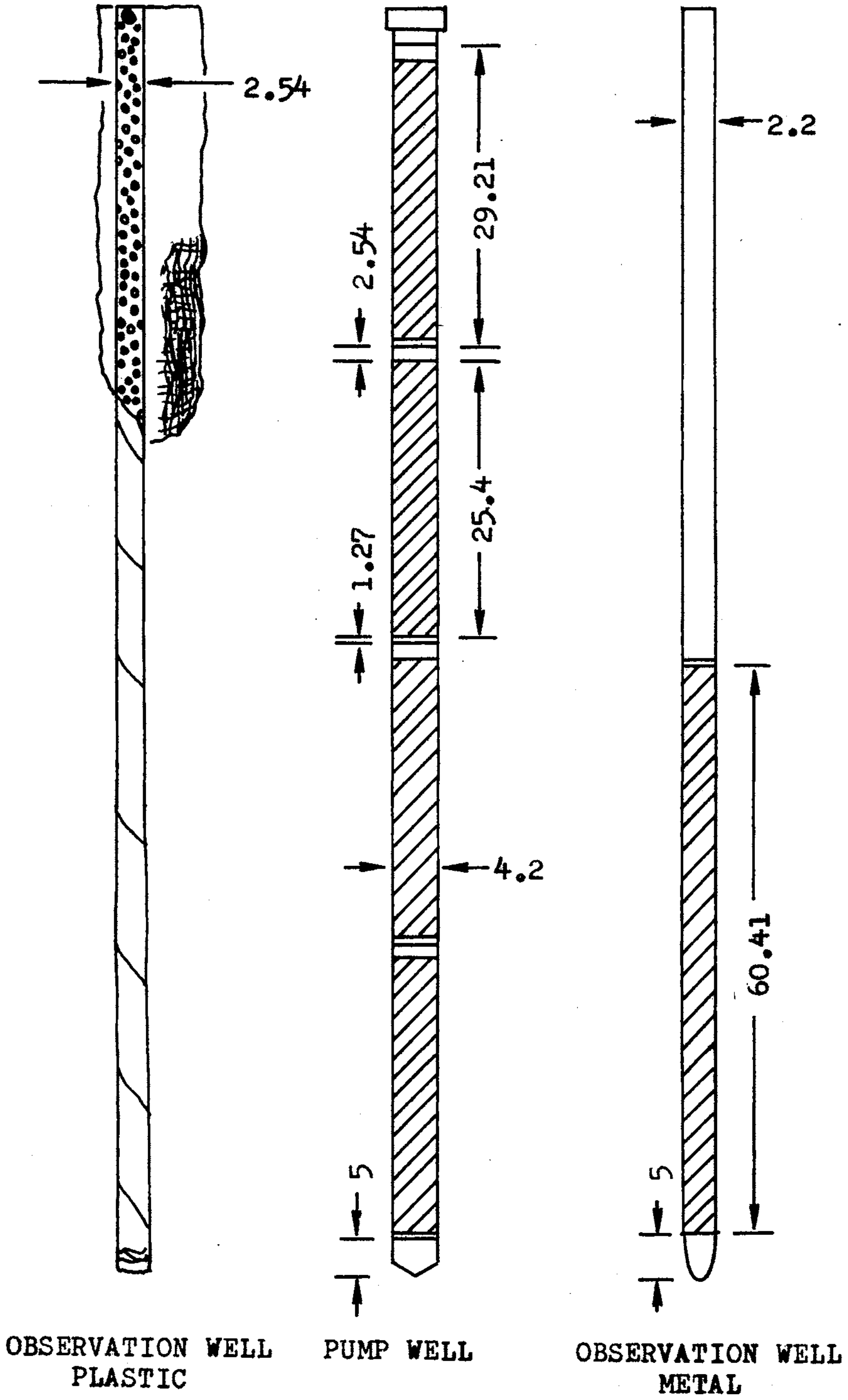


Figure 2. Dimensions of Wells (all dimensions in cm)

its end. See Figure 2 for dimensions. There were three observation wells made from lengths of 2.54 cm plastic pipe. This pipe was perforated by closely spaced 1/4 inch holes drilled at random for its entire length. The pipe was then wrapped in gauze in order to retard infiltration of sand particles into the well.

Model number one had the pump well and the metal observation well. The general configuration of the model is shown in Figure 3 and the dimensions of its parts in Figure 4. The sand layers were placed in the model surrounding the wells. The outer tank had a plug closing an opening in the center of its bottom. This created a 2.54 cm conical raised area on which the pump well was placed. The water levels in the observation well and the annular space were monitored using the manometer principle. The outlet at the bottom of the outer tank was connected to a length of 6 mm glass tubing by rubber tubing. A length of rubber tubing was inserted into the observation well for its entire length. This tubing was then connected to another length of glass tubing. The glass tubes were placed with their ends even with the bottom of the model (see Figure 3). When the manometers formed by the tubing were filled with water, the levels of the water in the annulus and the observation well were shown by the levels of the water in the glass tubes.

Model number two was a refinement of the first model. Three observation wells were added to the model. All the wells, including the pump well, were attached to the manometers by 1/4 inch o.d. copper tubing inserted in the bottom of each well. The copper tubes were run to the bottom of the manometers as shown in Figure 5. The plug which caused the raised portion in the first model was removed. The bottom

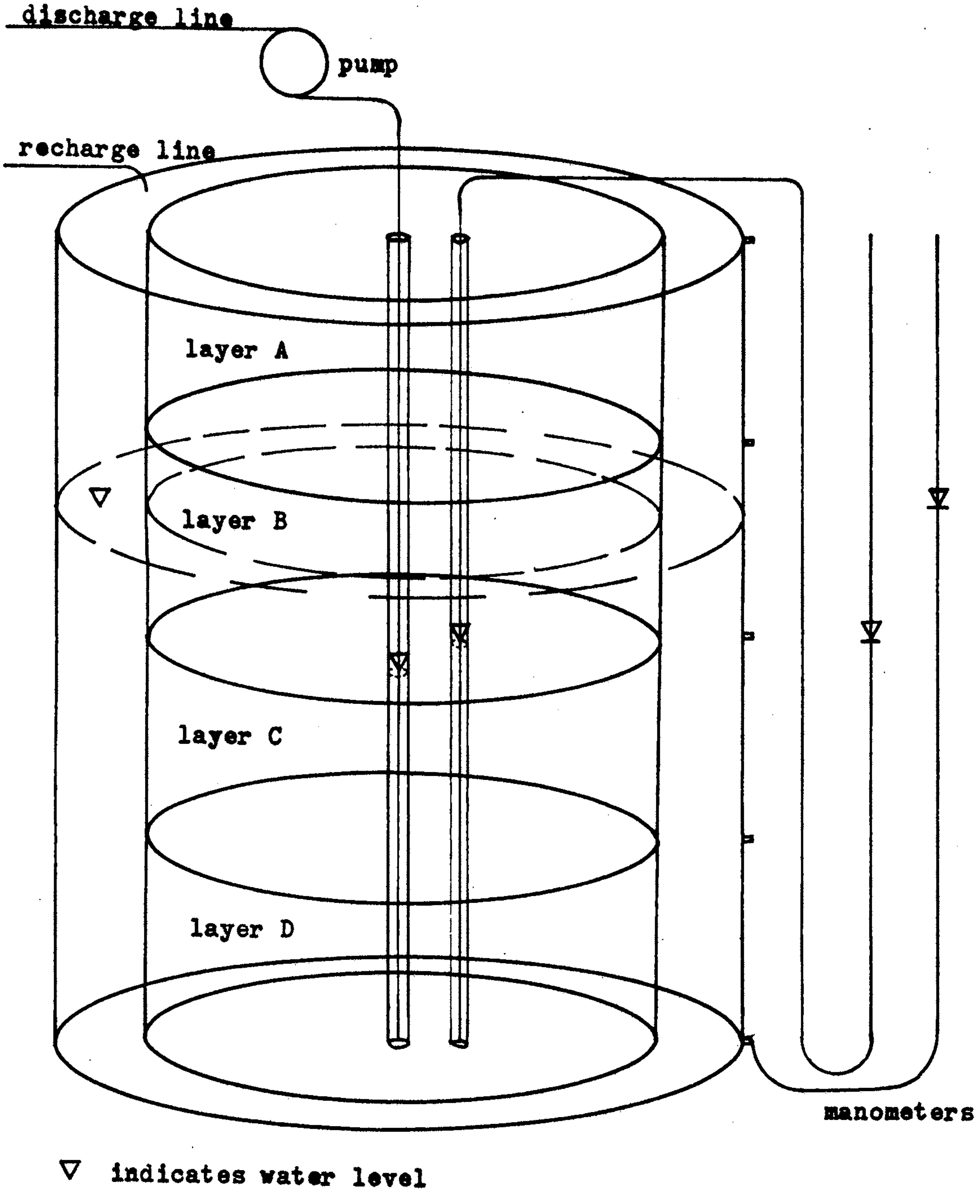


Figure 3. Diagram of Model Number One

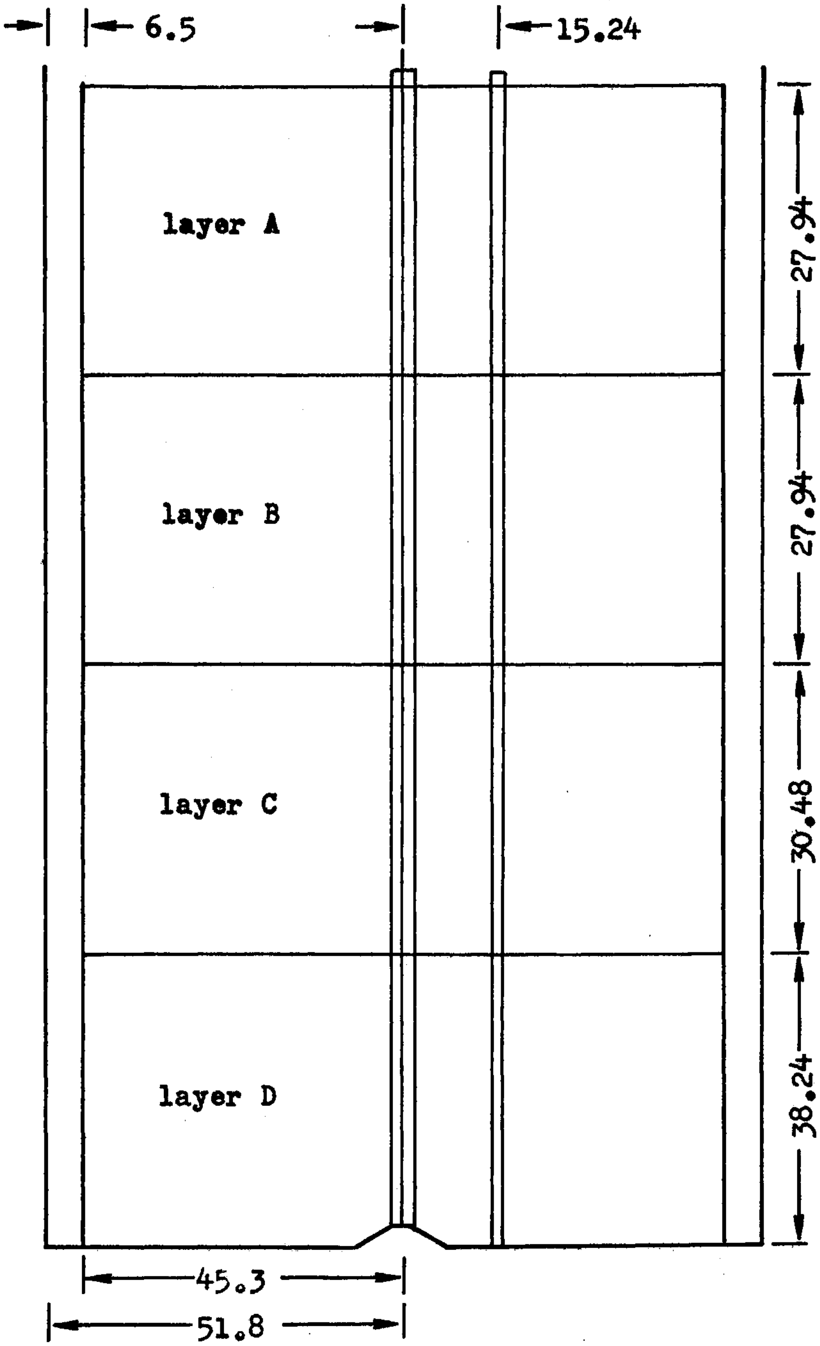


Figure 4. Dimensions of Model Number One (all dimensions in cm)

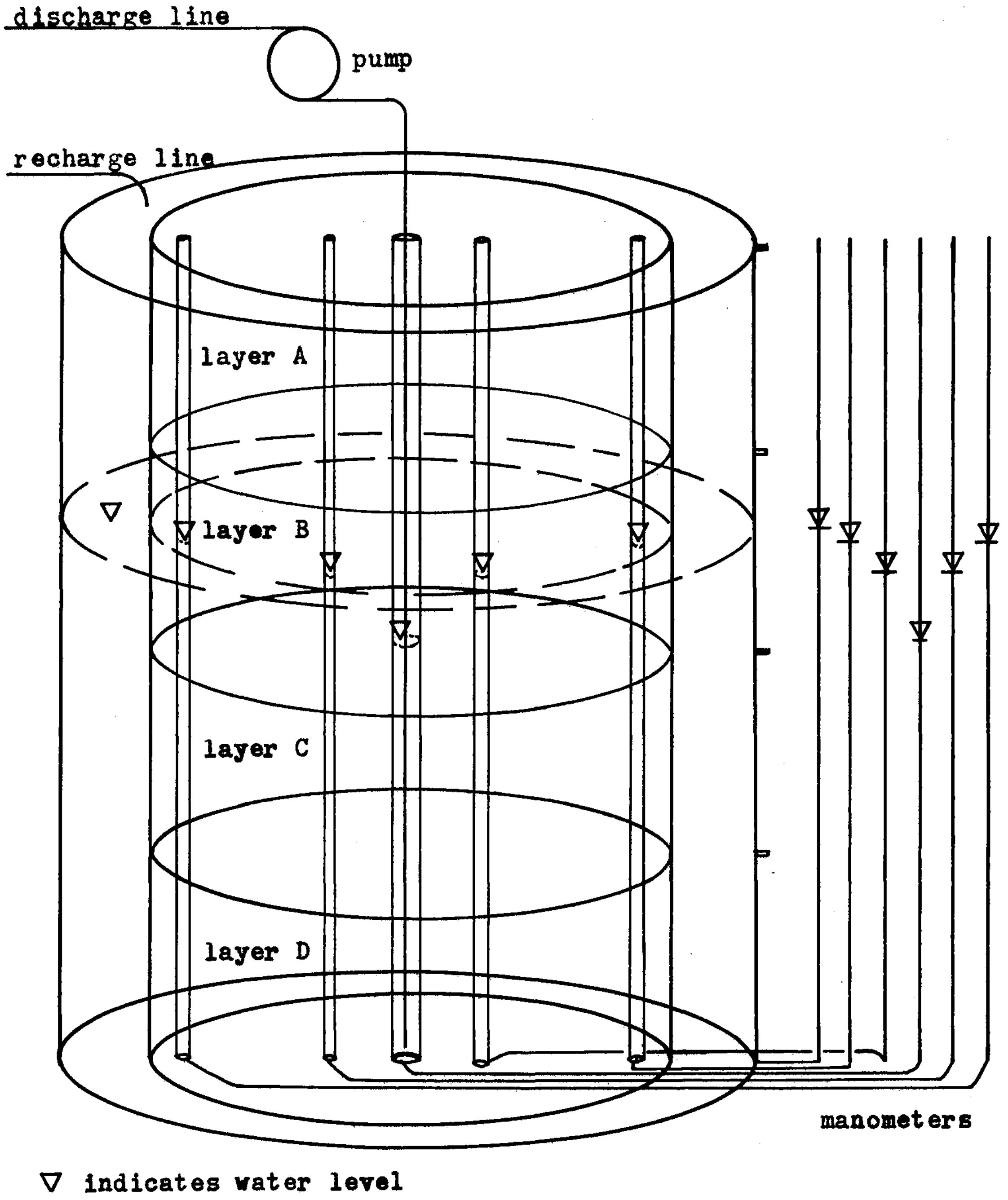


Figure 5. Diagram of Model Number Two

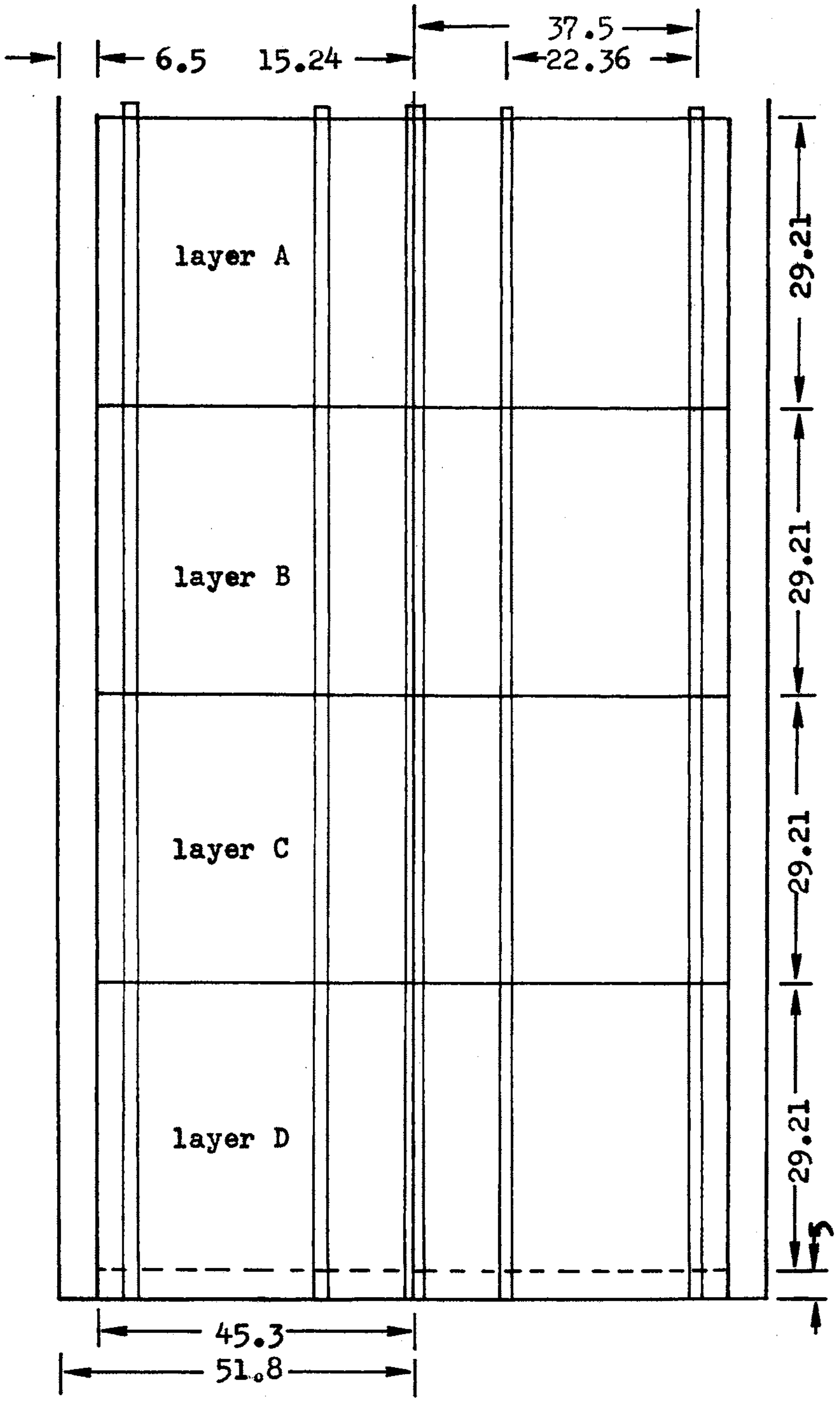


Figure 6. Dimensions of Model Number Two (all dimensions in cm)

layer of sand was then made 5 cm deeper than the three upper layers. This space was used to run the copper tubing for the manometers to the exterior of the model. The dimensions of the second model are shown in Figure 6.

Both models were filled by placing and tamping the dry sand into the inner tank. In the second model, each layer was wetted as it was being compacted. In both models the layer tops and bottoms were leveled, and the wells were set perpendicularly in the tank. In the first model the pump well was placed in the tank and the layers packed around it. The observation well in this model was hydraulically jetted into position. All the wells in the second model were held in position by a frame while the layers were compacted. In both models the wells were completed by surge pumping to remove any fine particles that had infiltrated through the screens or the gauze mesh.

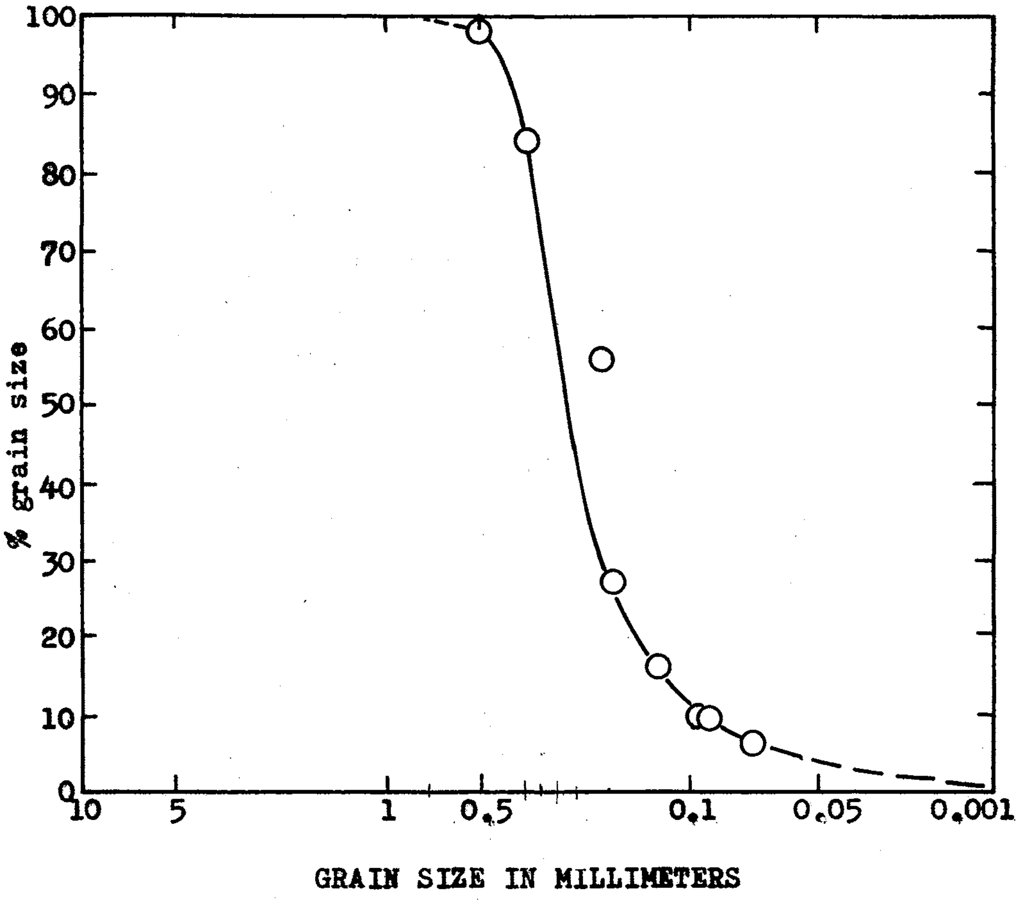
The pump used in testing the model was a Robins & Myers, type (CDQ), driven by a 1/6 horsepower, 115 volt a.c. motor. The pump was fitted with a recirculation line and two valves. The valves were used to reduce and regulate the flow from the pump.

Sands

In order to make the models as representative as possible of the layering in the Ogallala, sand samples from the formation were used in the construction of the models. Four types of sand were collected from an outcropping of the formation. The sampling site was located west of Guymon, Oklahoma, (NE 1/4, SW 1/4, Sec 2, T2N, R4E, C.M.) in Texas County. These sands were considered to be representative of the total interval of the aquifer. Laboratory analyses were performed to classify and determine the permeabilities of the sands.

Classification of the sands was based on analysis of data from a visual accumulation tube. The procedures used were those recommended in the Operator's Manual on the Visual Accumulation Tube (1958). First a sample of each sand was dried in an oven. Then the samples were weighed and wet-sieved through a number 230 mesh sieve. This was done to remove clay and silt particles. The material collected in the catch pan was then dried and weighed in order to determine the percentage of this type material present. The remainder of each sample was introduced into the visual accumulation tube. As the sample particles accumulated in the bottom of the tube, a recording of the depth was made. These recordings in the form of per cent of difference in grain sizes were used to plot the cumulative curves shown in Figures 7, 8, 9 and 10. The sands were then classified on the basis of their medium grain size (50% passing). The sands were lettered A, B, C, and D and were classified as medium, coarse and very coarse sands, respectively.

Permeability studies were conducted on a Soiltest Model K-670 high pressure permeameter for comparison with results from the sand model pump tests. Samples of the sands were taken as the second model was being constructed. This was done to make the samples representative of the disturbed sands being placed in the model. The samples were collected from eight locations in each layer as it was being placed in the model as shown in Figure 11. Each sample was given a coded number that identified its position in the model. In all, thirty-two samples were collected and tested on the permeameter. Both constant head and falling

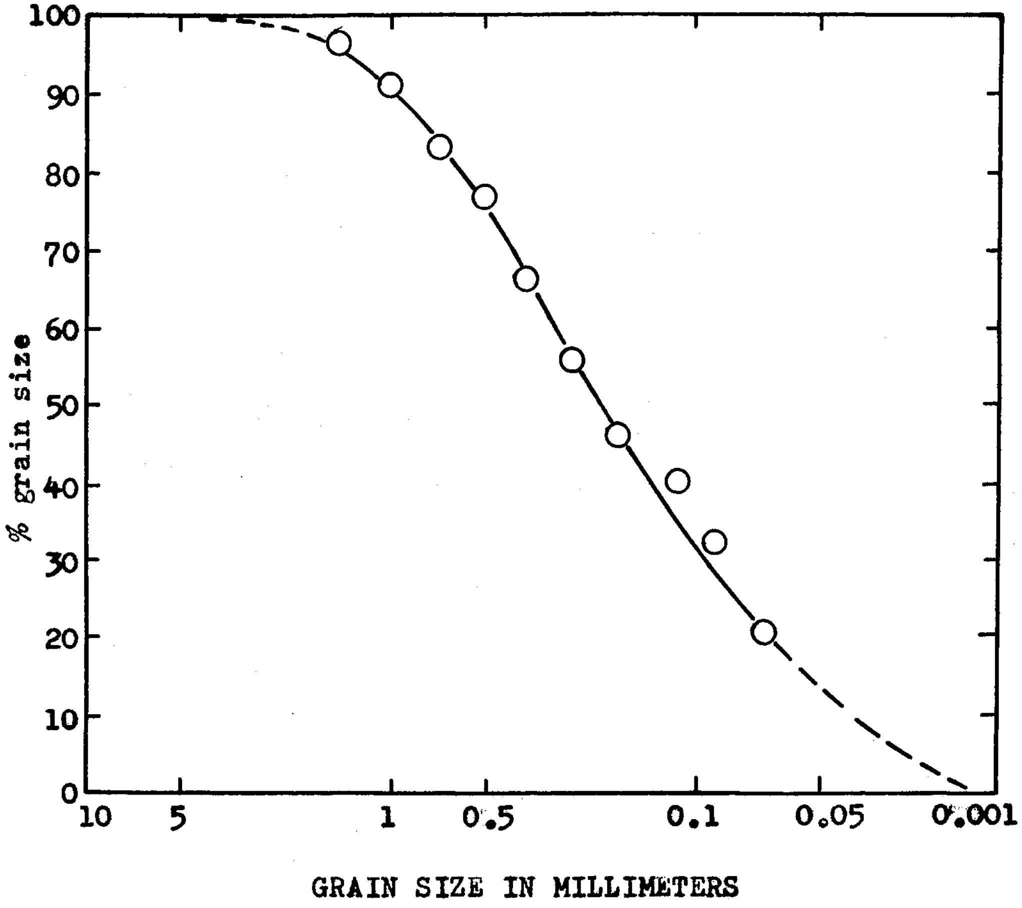


Wentworth's Size Classification

Greater than Coarse	V.C.	C.	M.	F.	V.F.	Silt & Clay

V.C. = Very Coarse
C. = Coarse
M. = Medium
F. = Fine
V.F. = Very Fine

Figure 7. Cumulative Curve, Layer A

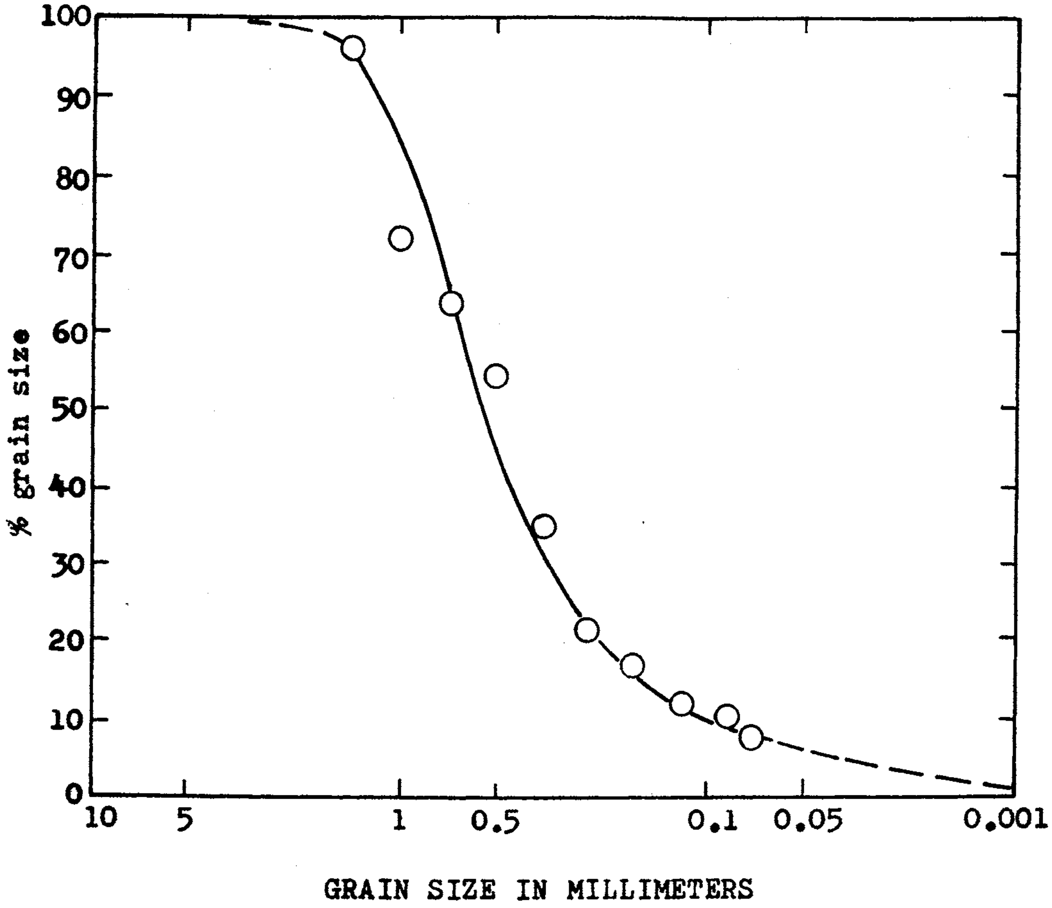


Wentworth's Size Classification

Greater than Coarse	V.C.	C.	M.	F.	V.F.	Silt & Clay

V.C. = Very Coarse
C. = Coarse
M. = Medium
F. = Fine
V.F. = Very Fine

Figure 8. Cumulative Curve, Layer B

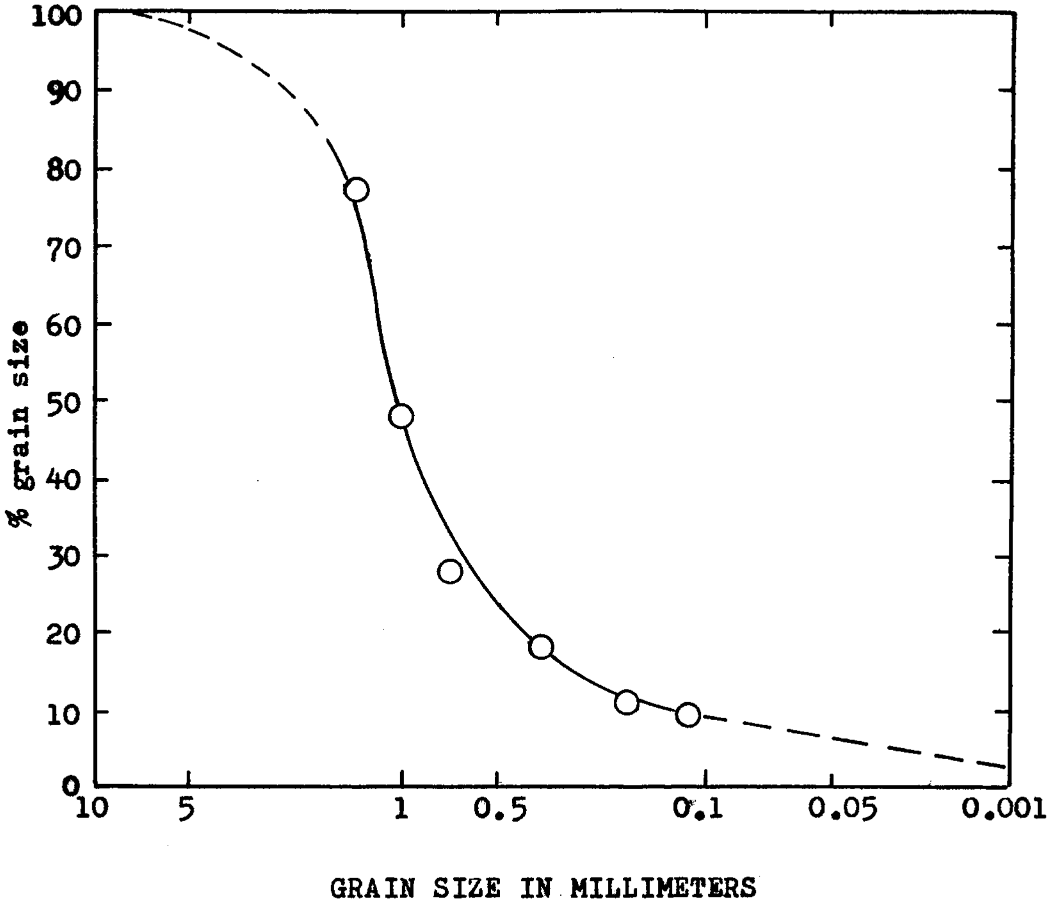


Wentworth's Size Classification

Greater than Coarse	V.C.	C.	M.	F.	V.F.	Silt & Clay

V.C. = Very Coarse
C. = Coarse
M. = Medium
F. = Fine
V.F. = Very Fine

Figure 9. Cumulative Curve, Layer C

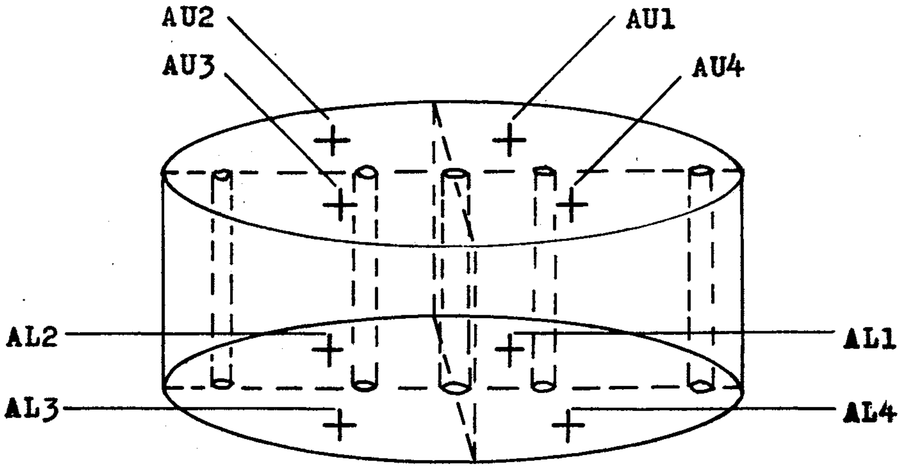


Wentworth's Size Classification

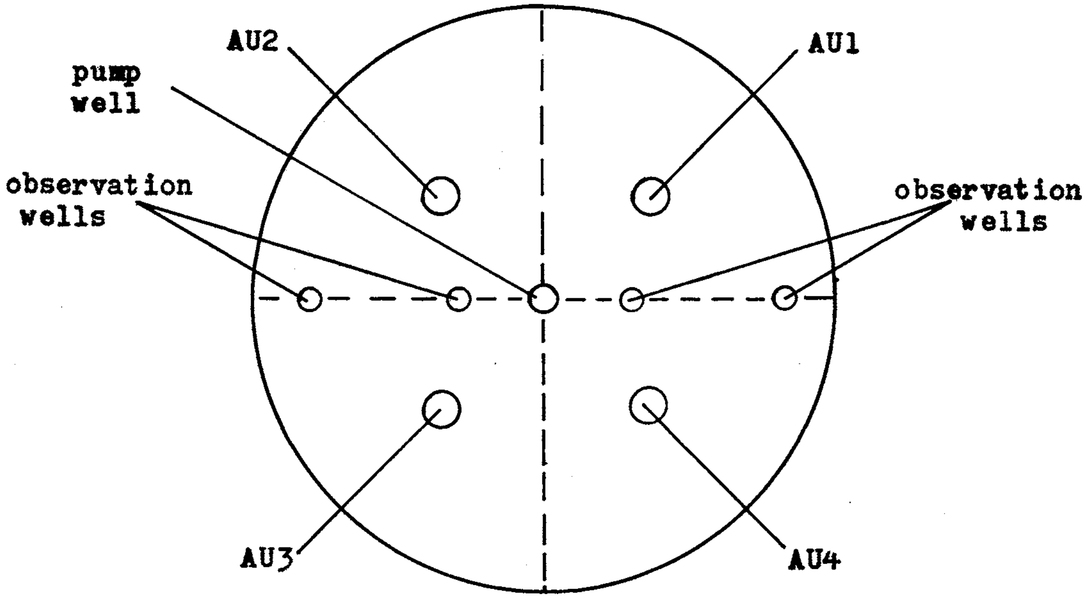
Greater than Coarse	V.C.	C.	M.	F.	V.F.	Silt & Clay

V.C. = Very Coarse
C. = Coarse
M. = Medium
F. = Fine
V.F. = Very Fine

Figure 10. Cumulative Curve, Layer D



Side View



Top View

A = Layer A

U = Upper Half of Layer

L = Lower Half of Layer

= Quadrant Number

Figure 11. Sampling Diagram

head methods were used for the analysis of each sample. The coefficient of permeability values was calculated using the following equations:

$$\text{Constant Head } K = \frac{QL}{AH} \tag{2.1}$$

where: K = coefficient of permeability, cm/sec

Q = rate of discharge, cm^3/sec

L = length of sample, cm

A = area of sample, cm^2

H = pressure head, cm.

$$\text{Falling Head } K = \frac{2.3aL}{AT} \log_{10} \frac{H_0}{H} \tag{2.2}$$

where: K = coefficient of permeability, cm/sec

a = cross sectional area of pipette, cm^2

L = length of sample, cm

A = area of sample, cm

T = time of test, sec

H_0 = pressure head at beginning of test, cm

H = pressure head at end of test, cm.

Results of the tests are tabulated in Table I.

Methods of Testing the Model

The procedures used in this study were formulated to obtain data for use in calculating the hydrogeologic coefficients of the model. This was accomplished by dewatering layers of the model by two different techniques. Pumping tests were performed as the first part of the study. The model was then tested by allowing each layer to drain by the action of gravity.

TABLE I

SAMPLE TEST K VALUES

Sample	Constant Head		Falling Head	
Number	cm/sec	gal/day/ft^2	cm/sec	gal/day/ft^2
AU1	------			
AU2	0.0018	38	0.0020	42
AU3	0.0011	23	0.0015	32
AU4	0.0012	25	0.0018	38
AL1	0.0003	6	0.0002	4
AL2	0.0008	17	0.0008	17
AL3	0.0015	32	0.0012	25
AL4	0.0005	11	0.0009	19
BU1	------			
BU2	0.0005	11	0.0014	30
BU3	0.0005	11	0.0012	25
BU4	0.0016	34	0.0019	40
BL1	0.0024	51	0.0025	53
BL2	0.0007	15	0.0011	23
BL3	0.0014	30	0.0015	32
BL4	0.0012	25	0.0031	66
CU1	0.0004	8	0.0015	32
CU2	0.0033	70	0.0031	66
CU3	0.0044	93	0.0048	102
CU4	0.0032	67	0.0034	72
CL1	0.0049	104	0.0064	136
CL2	0.0057	121	0.0061	129
CL3	0.0055	117	0.0061	129
CL4	0.0038	81	0.0042	89
DU1	0.0006	12	0.0012	25
DU2	0.0058	123	0.0071	151
DU3	0.0040	85	0.0033	70
DU4	0.0070	148	0.0076	161
DL1	0.0064	136	0.0069	146
DL2	0.0044	93	0.0032	68
DL3	0.0016	34	0.0019	40
DL4	0.0057	121	0.0064	136

Pump Tests

Model number one was used for the pumping tests. Each layer was tested separately by the two methods. First the pump well was operated while maintaining a static water level in the annular space at the top of a layer. The pump rate and the level of water in the observation well were the parameters monitored. The data obtained was used in a non-equilibrium and equilibrium formula for the calculation of transmissibility and storage coefficients. In the second portion of the test the water level in the annulus was allowed to fall as the pump well was operated. This data was used in calculating a storage coefficient for each layer, to compare with the value calculated from the first portion of the test. A description of the procedure used in the pumping tests follows.

Nonequilibrium and Equilibrium Portion of Test:

(1) Fill the annular space to capacity desired and keep full to allow saturation of the sand layer(s).

(2) Turn on pump, annulus recharge[1] and start timer. Monitor pump rate annulus water level and drawdown in observation well with respect to time.

(3) When drawdown stabilizes, hold there for 10 minutes.

(4) Turn off pump and continue to monitor annular level and drawdown in observation well.

(5) When drawdown has returned to original position, turn off recharge and timer.

---

[1] The desired level of water was maintained in the annulus by allowing the excess water from the recharge line to leave the model through the opening in the outer tank at the bottom of the layer being tested.

Storage Portion of Test:

(1) Fill the annular space to capacity desired and keep full to allow saturation of the sand layer(s).

(2) Turn on pump and start timer. Monitor pump rate, annular water level and drawdown in observation well with respect to time.

(3) When annular level reaches below next layer, turn off pump and timer.

(4) Repeat Nonequilibrium and Equilibrium Portion of Test and Storage Portion of Test for each layer.

Gravity Drainage Tests

The gravity drainage test was conducted with model number two. The data from this test were used in determining the specific yield of each layer. The procedure for this test is as follows:

Single Layer Test:

(1) Fill the annular space to capacity and keep it full to allow saturation of all four layers.

(2) Drain water from annulus through opening in outer tank at the interface between layer being tested and next lower layer. Measure volume water drained and note time and date.

(3) Monitor water levels in all manometers. When level reaches above interface again, drain and measure water collected noting time and date.

(4) Repeat (3) until the water level stabilizes at interface level in all manometers for 24 hours.

(5) Continue (2), (3), and (4) with next layer.

CHAPTER III

RESULTS

The data obtained from the methods previously outlined were used in determining the hydrogeologic coefficients of the models. These coefficients are defined as follows:

(1) Transmissibility (T) is defined as the rate of flow of water in volume per time through a unit vertical strip of the aquifer extending the full saturated thickness of the aquifer under a hydraulic gradient of 100 per cent (unit per unit) at the prevailing temperature of the water.

(2) Permeability (K) is a measure of the ease of movement of water through aquifers. The coefficient of permeability is defined as the rate of flow of water in volume per length of time through a unit cross sectional area of the aquifer under a hydraulic gradient of one unit per unit at the prevailing temperature of the water. The permeability is related to transmissibility by the aquifer thickness and is expressed as $T = Km$, where m is the aquifer's thickness.

(3) Coefficient of Storage (S) has been defined as the volume of water released or taken into storage per unit surface area of the aquifer per unit decline or rise of head.

(4) Specific Yield (Sy) is a measure of the water yielding capacity of the aquifer material and is expressed quantitatively as the percentage of the total volume of aquifer material occupied by the ultimate volume

of water released from or added to storage, in an aquifer per unit (horizontal) area of aquifer and per unit decline or rise of the water table. The coefficient of storage and specific yield have been considered to be equivalents in the water table case. Specific yield in this case is broken into two components, that amount of water released instantly from storage, and that released with time due to gravity drainage.

Figures 12, 13, 14, and 15 show plots of the water levels in the observation well, the annular space, and the pump rate versus time for the pumping tests of each combination of layers. Table II gives a listing of the drawdown with time for the nonequilibrium portion of the test for each layer. The equilibrium values for each test are also shown in Table II. Table III shows the data from the gravity drainage tests.

The values for T and S were calculated using adaptations of the formulas and techniques developed by Thies (1935) and Thiem (1906). The equations of Thies were applied to the nonequilibrium section of the first portion of the pump tests. An adaptation of Thiem's equation as explained by Marlette (1962) was used with the equilibrium section of the first portion of the pump tests. The second portion of the pump tests were used to calculate an empirical value for S, for comparison with that obtained from Thies's and Thiem's equations.

The Thies equations were used to calculate T and S first. These equations for unsteady conditions are expressed as:

$$s = \frac{114.6\ Q}{T} \quad W(u) \tag{3,1}$$

and

$$u = \frac{1.87\ r^2 S}{Tt} \tag{3.2}$$

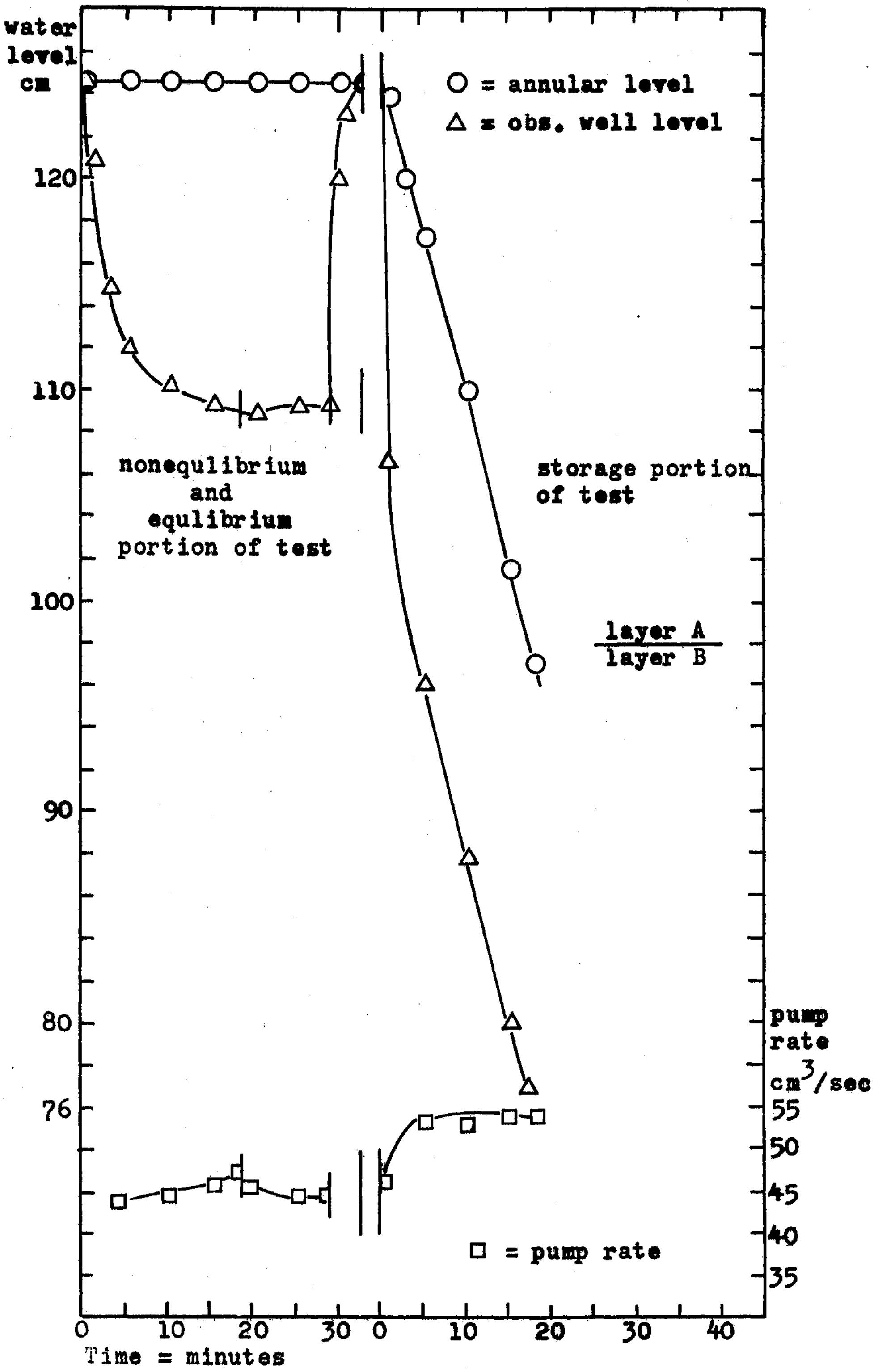


Figure 12. Pump Test Data, Layers A, B, C, D

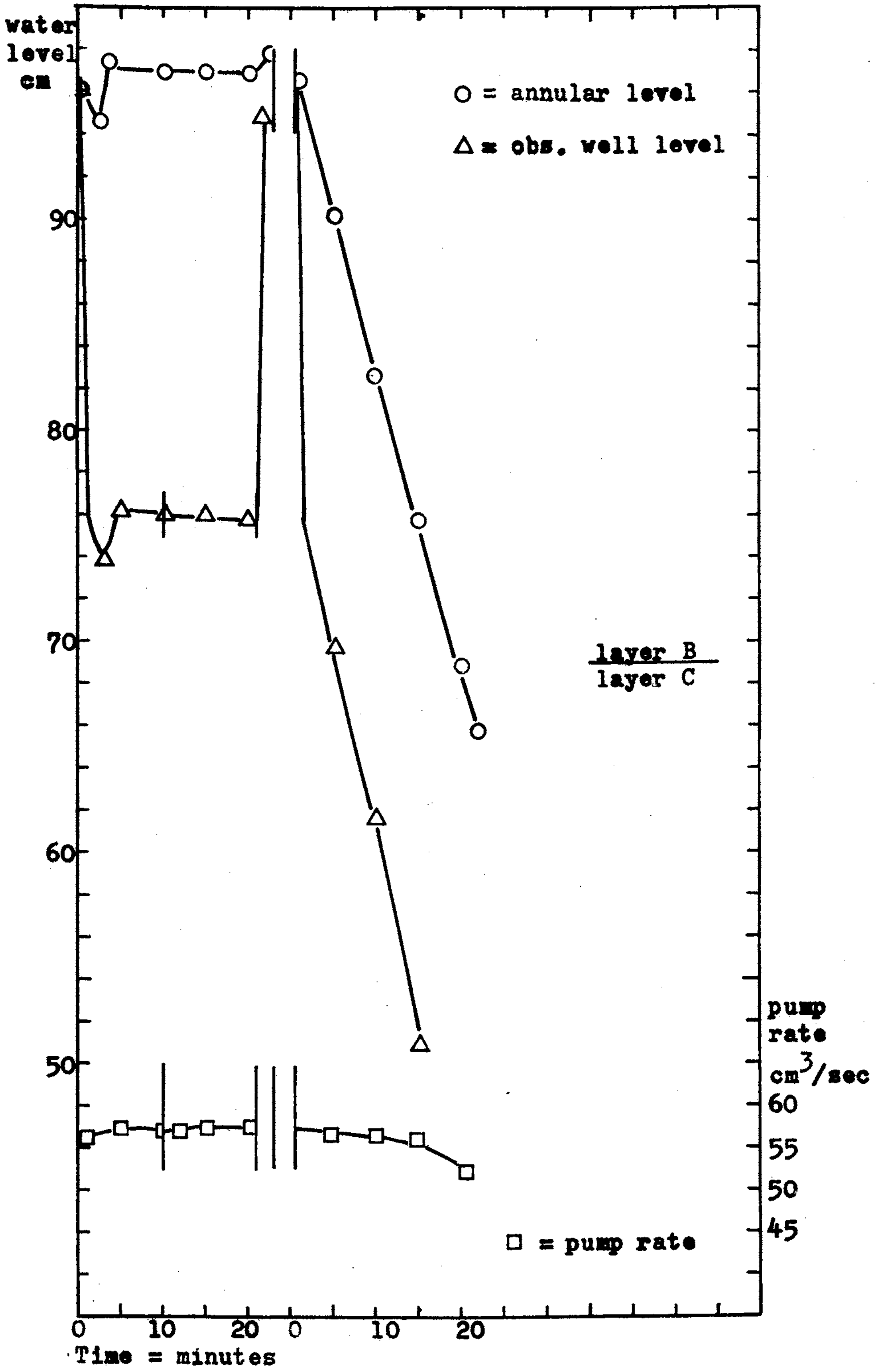


Figure 13. Pump Test Data, Layers B, C, D

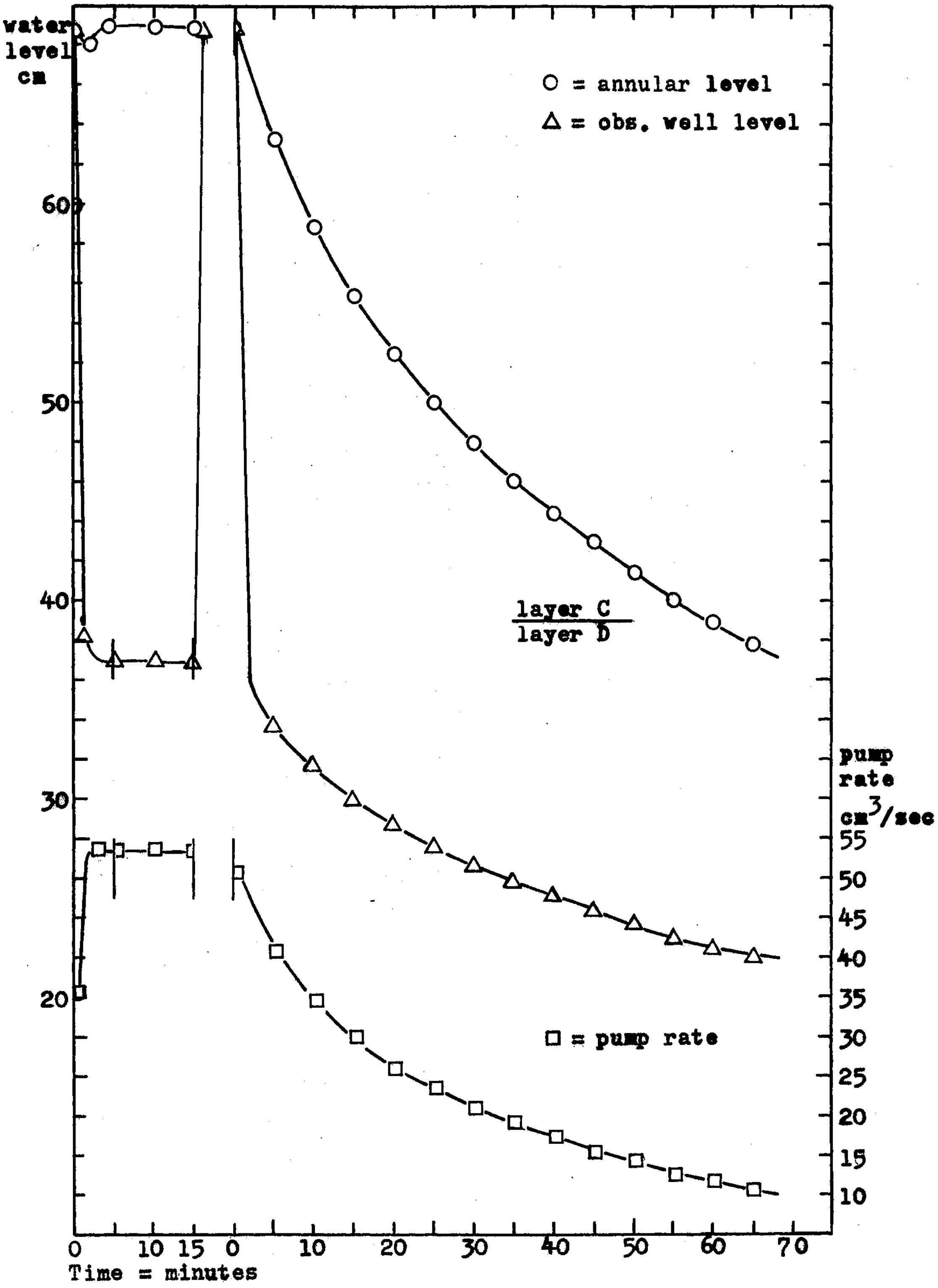


Figure 14. Pump Test Data, Layers C, D

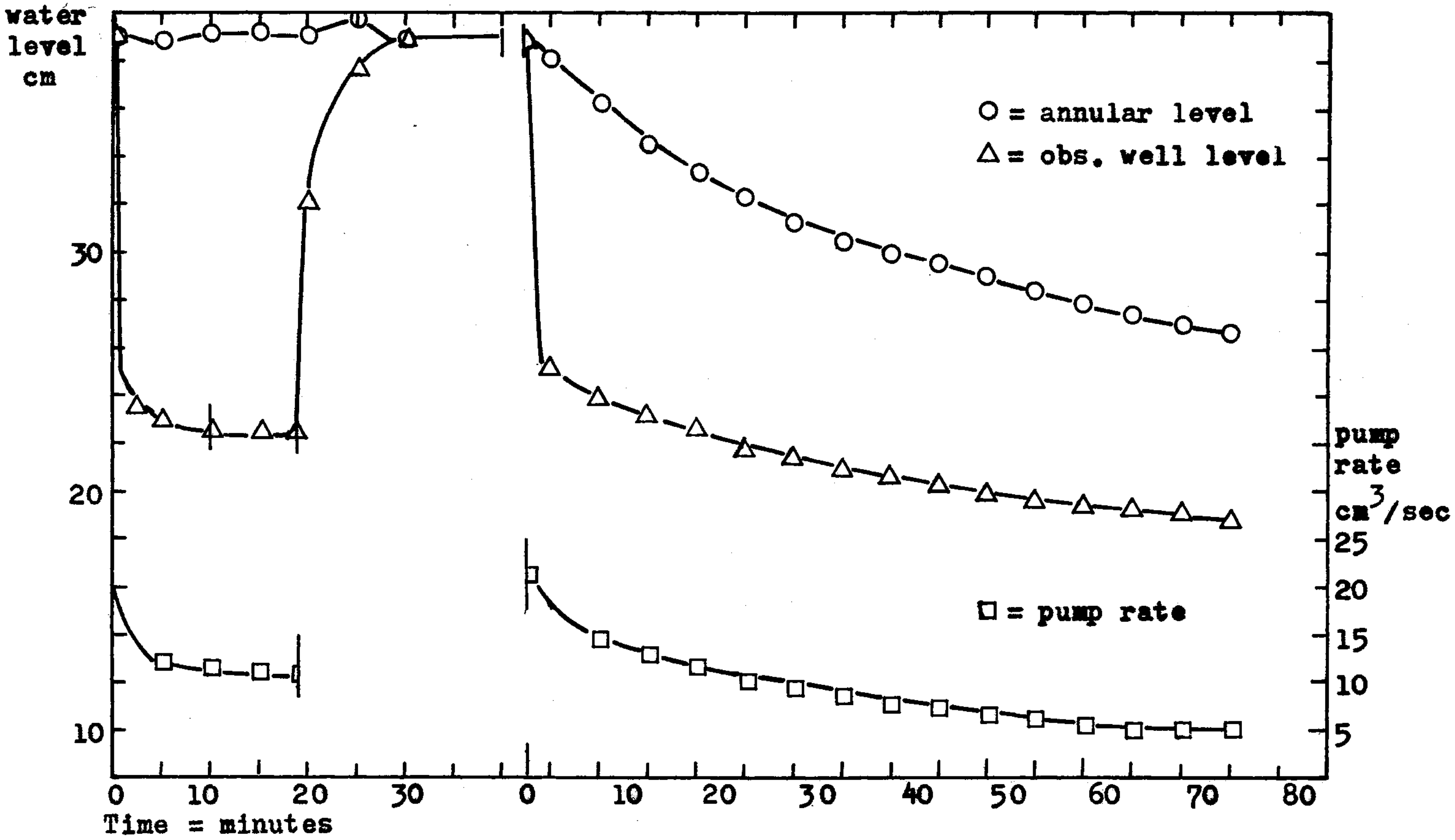


Figure 15. Pump Test Data, Layer D

TABLE II

DRAWDOWN AND TIME VALUES-NONEQUILIBRIUM

layers A,B,C,D				layers B,C,D		layers C,D		layer D	
t	s	t	s	t	s	t	s	t	s
0	0.0	210	10.6	0	0.0	0	0.0	0	0.0
20	0.9	215	10.8	5	4.0	5	3.71	10	8.4
25	1.3	240	11.4	10	9.7	10	9.82	15	11.3
30	1.7	270	11.8	15	13.3	15	14.43	20	12.8
35	2.0	300	12.5	20	15.4	20	18.24	25	13.2
40	2.2	330	12.8	25	16.7	25	21.3	30	13.4
45	2.7	360	13.1	30	17.8	30	24.35	35	13.9
50	3.1	390	13.4	35	18.5	35	25.32	40	14.0
55	3.5	420	13.7	40	19.0	40	26.79	60	14.1
60	3.8	450	13.8	45	19.4	45	27.86	80	14.3
65	4.2	480	14.0	50	19.65	50	28.75	100	14.4
70	4.5	510	14.1	55	19.80	55	29.5	120	15.5*
75	4.9	540	14.25	60	20.00	60	30.37	140	15.5
80	5.3	570	14.35	65	20.1	65	30.74		
85	5.5	600	14.45	70	20.2	70	31.21		
90	5.9	630	14.5	75	20.3	75	31.38		
95	6.15	660	14.6	80	20.4	80	31.55*		
100	6.4	690	14.7	85	20.4	85	31.50		
105	6.7	720	14.75	90	20.6	120	31.50		
110	6.9	750	14.8	95	20.6				
115	7.1	780	14.95	100	20.9				
120	7.4	810	15.05	110	21.05				
125	7.7	840	15.1	115	21.05				
130	7.9	870	15.2	120	20.2				
135	8.2	900	15.3	210	20.7				
140	8.4	930	15.4*	240	20.5				
145	8.6	960	15.4	270	20.6				
150	8.8	990	15.5	300	20.7*				
155	9.0	1000	15.4	330	20.7				
160	9.3			360	20.7				
165	9.4			390	20.7				
170	9.5								
175	9.6								
180	9.8								
185	10.0								
190	10.2								
195	10.3								
205	10.5								

t = time in seconds
s = drawdown in centemeters
* = equlibrium point

TABLE III

GRAVITY DRAINAGE DATA

layer A		layer B		layer C		layer D	
volume	hour	volume	hour	volume	hour	volume	hour
60,000 ml	1	68,900 ml	1	68,000 ml	1	75,000 ml	1
3,000	24.5	4,200	24	4,340	12	14,050	11
2,000	50.5	2,280	47	2,680	24.5	5,400	25
				1,500	35	2,260	48
				1,280	47.5	2,700	77
				1,900	71	1,180	101
				840	82.5	800	120
				1,880	96.5	800	144
				1,370	107.5	600	168
				560	123.5	1,180	196
				700	148.5		
65,000 ml		75,380 ml		85,050 ml		103,970 ml	

where: s = drawdown, ft

v = distance from pumped well to observation point, ft

Q = discharge, gpm

t = time after pumping started, days

S = coefficient of storage, fraction

W(u) = "well function", exponential integral

u = lower limit of integration.

Because mathematical difficulties in calculating values for W(u) and u are encountered, investigators have developed graphical solutions for use in estimating the desired answers. A plot on logarithmic paper of values of W(u) versus u for a wide range of u values is prepared as a "type curve". Plots of drawdown versus time are made on the same size logarithmic paper for the data from the well being tested while under unsteady conditions. The observed data curve is superimposed on the type curve, keeping the co-ordinate axes of the two curves parallel, and adjusted until a position is found by trial whereby most of the plotted points of the data fall on a segment of the type curve. An arbitrary point is selected on the coincident segment and the co-ordinates of this matching point are recorded. The values of W(u), w, s, and t thus determined are used in Equations (3.1) and (3.2) to calculate T and S.

Thies's nonequilibrium equations are usually associated with a nonleaky infinite and isotropic artesian aquifer of constant thickness with fully penetrating wells and constant discharge, during the period of unsteady conditions. However, this equation has been applied to the first portion of well pumping tests of water table aquifers by Walton (1970). Walton also includes a method for accounting for the increase in storage due to delayed gravity drainage. The pump tests of the model are of such a short duration that delayed drainage is not a problem in the nonequilibrium portion of the pumping test. This was demonstrated by the gravity drainage test, in which the effects of drainage in each layer were slow in appearing.

The curves used in determining W(u) and u are shown in Figure 16. The values for T and S calculated by this method are listed in Table IV at the end of this chapter.

Values for the permeability K were calculated from the laboratory studies of the sands (previous chapter) and from Thiem's equation:

$$K = \frac{Q}{2\pi sm} \ln \frac{r_2}{r_1} \qquad (3.3)$$

where: K = permeability, cm/sec

Q = discharge, ml/sec

s = drawdown at equilibrium in obs. well, cm

m = saturated thickness, cm

r_1 = distance to obs. well, cm

r_2 = distance to recharge boundary, cm.

Because the well is located in the center of the tank, the drawdown at the well face may be calculated by using a different form of the same equation:

$$s = \frac{Q(2.3)(\log \frac{r_2}{r_0})}{2\pi(K)(m)} \qquad (3.4)$$

where: r_0 = radius of pump well, cm

r_2 = distance to recharge boundary, cm.

Equation (3.3) was used with the equilibrium data to calculate values of K for each layer combination. Values of K calculated from the laboratory

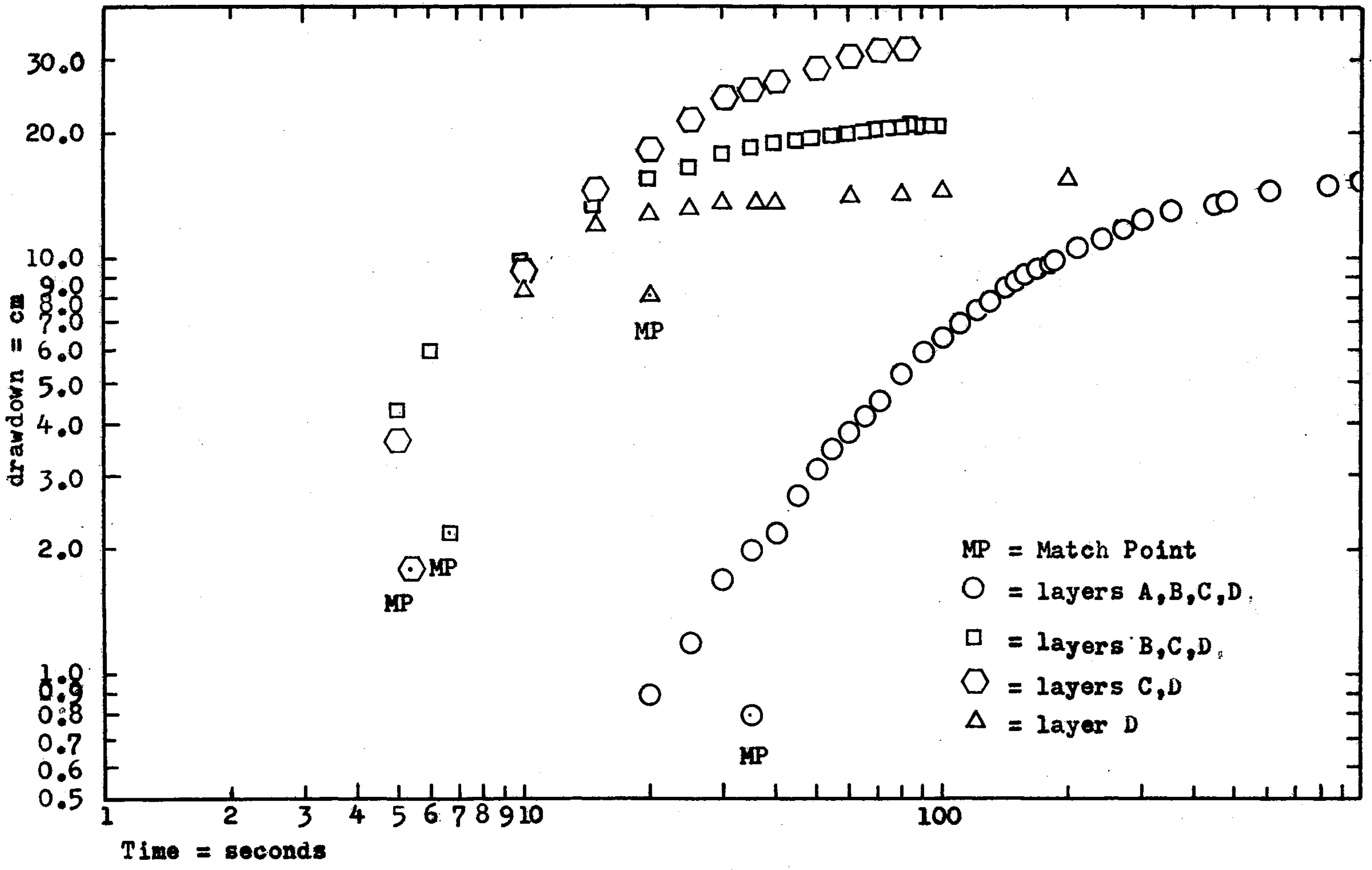


Figure 16. Nonequelibrium Curves

data were used for comparison with the values from Thiem's formula. Equation (3.4) was used to predict the drawdown in the pump well. These values were plotted along with the observed equilibrium values as shown in Figure 18 of the next chapter. The values are listed in Table IV.

The storage portions of the pump tests were used to calculate empirical storage coefficients for layer combinations. For each layer dewatered, the amount of water removed from storage in the aquifer is given by:

$$V_w = \text{Volume of } Q\ t - (A_v + W_v) \tag{3.5}$$

where: V_w = Volume of water removed from a layer, ml

Q = pump rate, cm^3/sec

t = duration of test, sec

A_v = amount of water from annular space, cm^3

W_v = amount of water from pump well and obs. well, cm^3

The tests for each layer were not continuous with respect to time. Therefore, V_w values for layer combinations must be calculated and summed in reverse sequence, i.e., D, C, B, and A. The amount of water removed prior to equilibrium must be subtracted from the lower layer(s) in each sequence to allow for the lack of initial drawdown. Using this method, S values can be calculated for layer combinations as follows:

$$S = \frac{V_w + \Sigma(V_w - v)}{V_m - W_s} \tag{3.6}$$

where: S = storage coefficient, dimensionless

V_w = volume of water removed from a layer, cm^3

v = volume of water removed prior to equilibrium, cm^3

V_m = volume of layers in combination, cm^3

W_s = volume of spaces occupied by wells, cm^3.

The storage coefficients for each layer are listed in Table IV.

The values for specific yield were calculated from the gravity drainage study. The calculations were made based on the formula:

$$Sy = \frac{V_w}{V_m} \tag{3.7}$$

where: Sy = the dimensionless Specific Yield value; due to gravity drainage

V_w = volume of water drained from a layer, cm^3

V_m = volume of the material in the layer, cm^3.

The amount of water contained in the annulus and wells of the model was subtracted from the volume of water drained from a layer as it was not actually stored in the aquifer material. Also, the volume occupied by the wells had to be subtracted from the volume of the aquifer material. Also, the volume occupied by the wells had to be subtracted from the volume of the aquifer material, given by:

$$Sy = \frac{V_w - (A_v + W_v)}{V_m - W_s} \tag{3.8}$$

where: A_v = volume of water from annular space, cm^3

W_v = volume of water from all wells, cm^3

W_s = volume occupied by wells in the model, cm^3.

The amounts of water removed for each time period were tabulated and totaled (see Table III). Because all the layers of model number two were of the same thickness, the same general formula was used to calculate the specific yield of each layer. The calculated values are listed in Table IV. A plot of the specific yield versus time appears in Figure 17.

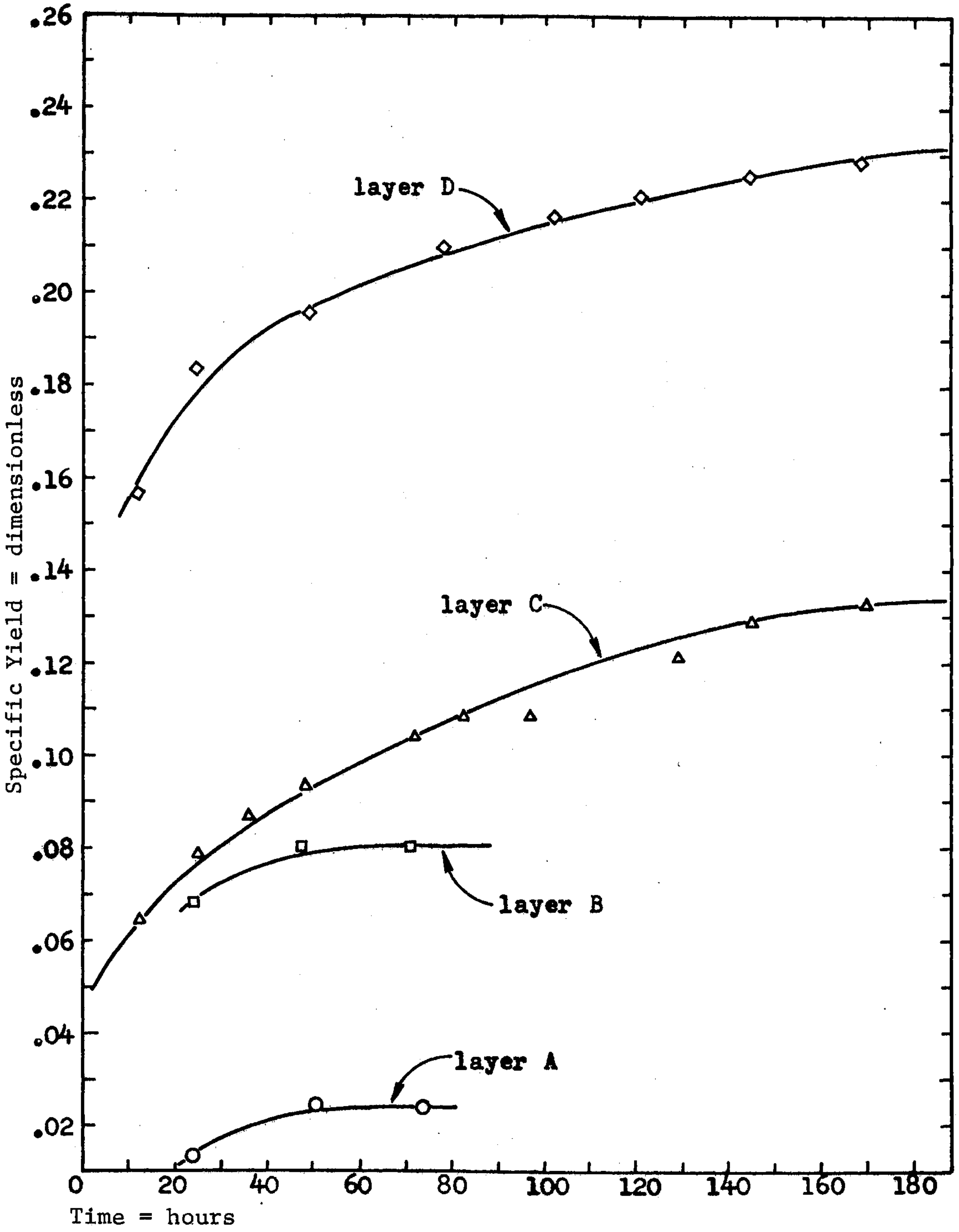


Figure 17. Specific Yield Versus Time

TABLE IV

CALCULATED VALUES

layers or layer	K= gal/day/ft^2			T = gal/day/ft		S = dimensionless		S_y = dimensionless
	samples	Thiem	Thies	samples	Thiem	Thies	pump test	gravity drainag
A,B,C,D	310	330	320	279	80	0.28	0.004	
B,C,D	290	300	120	252	100	0.05	0.11	
C,D	260	190	150	220	90	0.02	0.17	
D	160	80	160	120	60	0.01	0.06	0.266
A	24			27				0.025
B	32			30				0.081
C	100			100				0.130

CHAPTER IV

CONCLUSIONS

The methods described in the previous chapter were used to derive the values of the hydraulic properties of the sand layers and their combinations in the model. These were all expressed in gallons, days, and feet so they would be relevant to field studies or computer model studies. Table IV, in the preceding chapter, shows a listing of all the values determined.

The sample test permeabilities and the gravity drainage specific yield values were the only parameters not determined from pump test data. With the exception of the pump test values for layer D, they were also the only properties not determined from tests of layer combinations. The transmissibilities and storage fractions were calculated from the pump test data of layer combinations. In order to make comparisons of the single layer properties with the characteristics of the layers in combination, the permeability of each layer was used to predict the transmissibility of that layer in the model. An analysis of these predicted values and the values derived from the pump test data was made. From this it is concluded that the transmissibilities of layers in combinations are approximated by a summation of the layer transmissibilities. Table V shows a comparison of the values from the pump tests and the summations of the predicted values from each layer.

TABLE V

TRANSMISSIBILITIES

	~~T~~K = gal/day/ft^2 - for layer(s) :			
	A,B,C,D	B,C,D	C,D	D
Predicted by sample tests	310	290	260	160
Thies - nonequilibrium	320	120	150	160
Thiem - equilibrium	330	300	190	80

The transmissibilities from the nonequilibrium data were dependent upon utilizing the best fit of the data to a type curve. The results of this method would be suspect in an evaluation of reliability. However, the transmissibilities calculated from the Thies equations (3.1 and 3.2) and this data were of the same magnitude as those predicted by the summations of the layer transmissibilities. The values from the Thiem equation (3.3) were also in the range of those from the other two methods (see Table V). This indicates that the value for each layer as used in the Texas Tech computer model would not give the best results when used to make an estimate of the average permeability for the homogeneous approach. A value of 80 gpd/ft^2 was calculated when the Thiem equation was used with data from the author's study. From this and the transmissibility predictions for the model, it is concluded that a better representation of the formation might be to hold the permeability of each layer constant and allow the transmissibility to change as the formation is dewatered. Also the use of the lower values for the permeabilities of the layers as shown in Table V should be used.

The storage fractions shown for the pump tests in Table IV were not consistent enough to make any valid recommendation as to the magnitude of the value that should be used. The tests run on the model were not of sufficient duration to obtain good data for making this estimate and the storage portion of the pumping tests was poorly designated. The values from the nonequilibrium part of the pump tests were again dependent upon the fit of the type curve to the data. Under water table conditions, a portion of the water released from the storage is due to the action of gravity. In the tests run on the first model, the pump rate was too great to allow time for this release to appear. This is evident in the specific yield versus time graph in Figure 17, Chapter III. During this one hour period only slightly more water than that contained in the wells and annular space could be accounted for. The time required, with respect to the volume of water obtained, was longer than the time required to pump test each layer combination. This indicates that insufficient time was given for accurate results.

Also, there is a question as to which layers were contributing water to the pump test. Inasmuch as the drawdown at the well face was so great as to penetrate more than one layer during pump test of each layer combination, and because the lower layers of the model had a greater transmissibility, they might have been expected to allow a greater volume of water to pass through during the dewatering of the upper level layers, thus creating a short-circuiting effect wherein the lower layers were over responding to the head gradient created during the initial stage of pumping.

The Thiem equation (3.4) would predict a drawdown similar to that shown in Figure 18 for the beginning of each test. This condition was demonstrated during unrecorded pump tests of the second model. From these tests it was logical to assume that this was occurring during the tests of the first model. This caused some difficulty in determining empirical values for the storage fraction from the dewatering portions of the pump tests. These tests were not continuous with time, making the use of summations of individual tests necessary. Determining which part of each test was to be used was purely speculation. The values calculated by this technique are shown in Table IV in the previous chapter. As can be seen, they are not consistent or realistic and as such were disregarded.

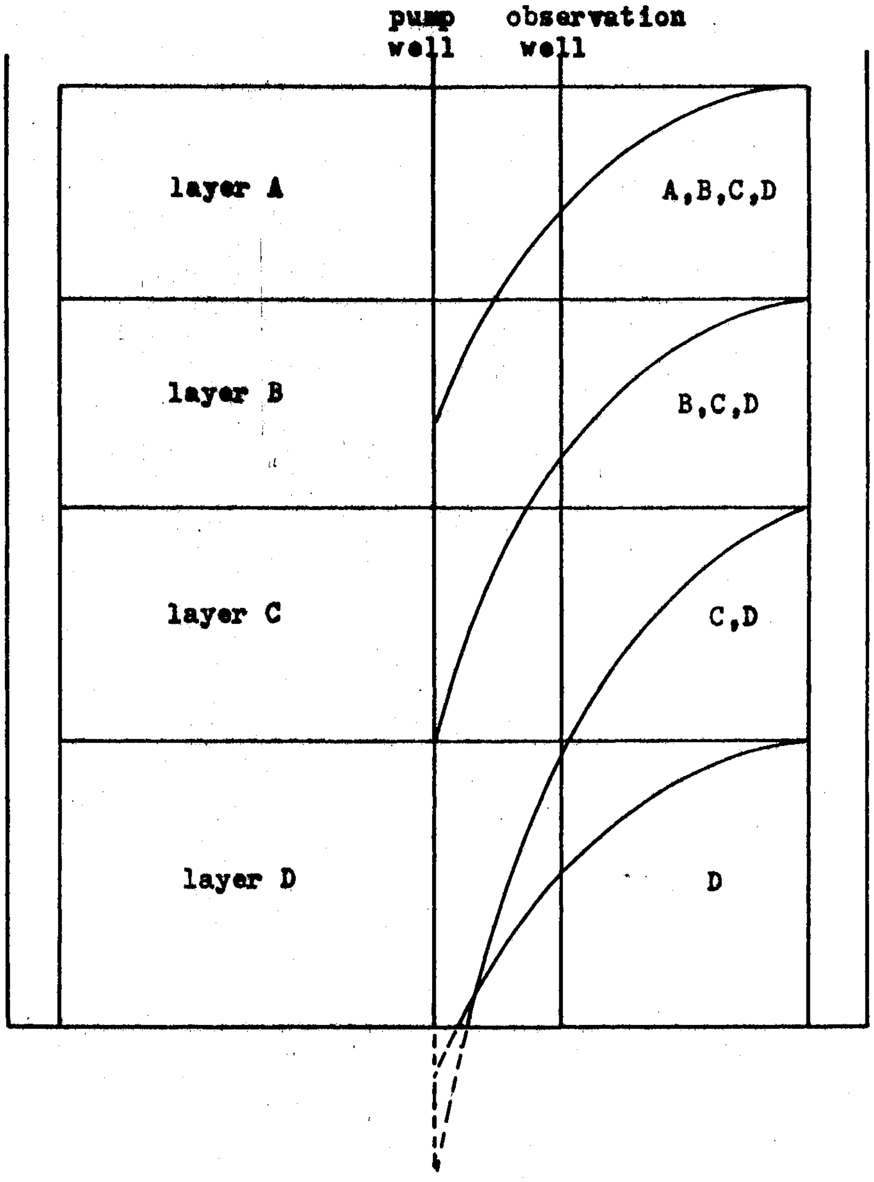


Figure 18. Thiem Drawdown Predictions

The average of the specific yield values from the gravity drainage test was 0.13. The Texas computer model used an average of 0.16. This value was derived from actual pump tests data and was used as in a homogeneous case. In using a layered approach to computer modeling of the formation, DeVries and Kent (1972) used a weighted averaging technique to calculate S values for each layer. Using this technique, they estimated the S values to be 0.07, 0.11, 0.17, 0.25 for layers A, B, C, and D. The author's study would suggest values of 0.03, 0.08, 0.13, and 0.27 be used as empirically derived values rather than intuitively calculated values.

CHAPTER V

RECOMMENDATIONS FOR FUTURE TESTS

Further studies should be made using the second model in order to refine the values for each parameter. This model should give better results as the addition of the three observation wells would allow a better definition of the water levels during the pumping periods. If further studies are made, a pump with a lower discharge rate should be used. This would make each test longer and thus allow a more reliable estimate of the storage fraction. A continuous pump test of the entire model over an extended period of time would also make an empirical estimate of the storage fraction easier and more accurate. Tracer studies might also be made to determine the origin of water withdrawn during the pumping.

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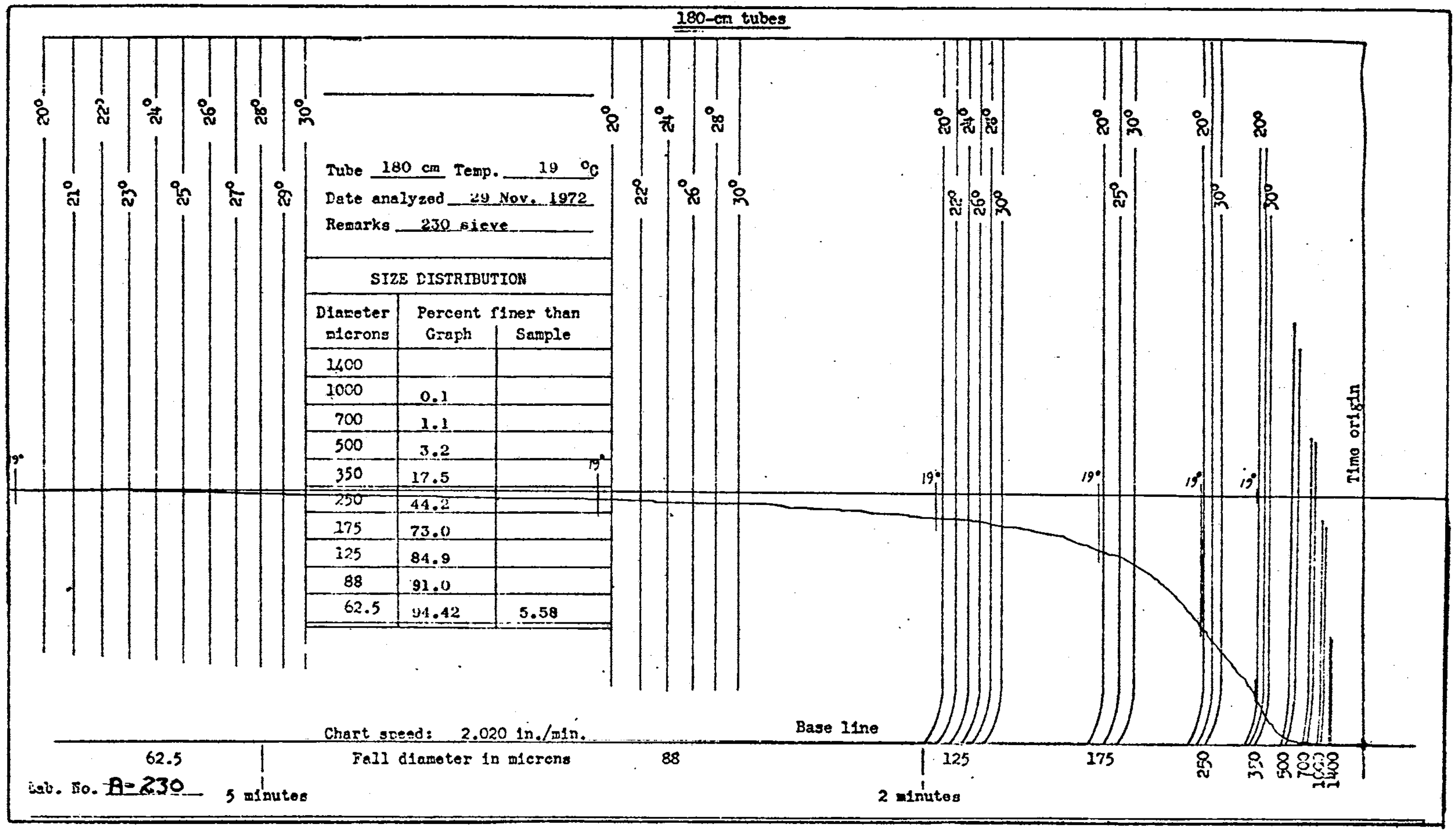
APPENDIX A

VISUAL ACCUMULATION TUBE CHARTS



Tube 180 cm Temp. 19 °C

Date analyzed 29 Nov. 1972

Remarks 230 sieve

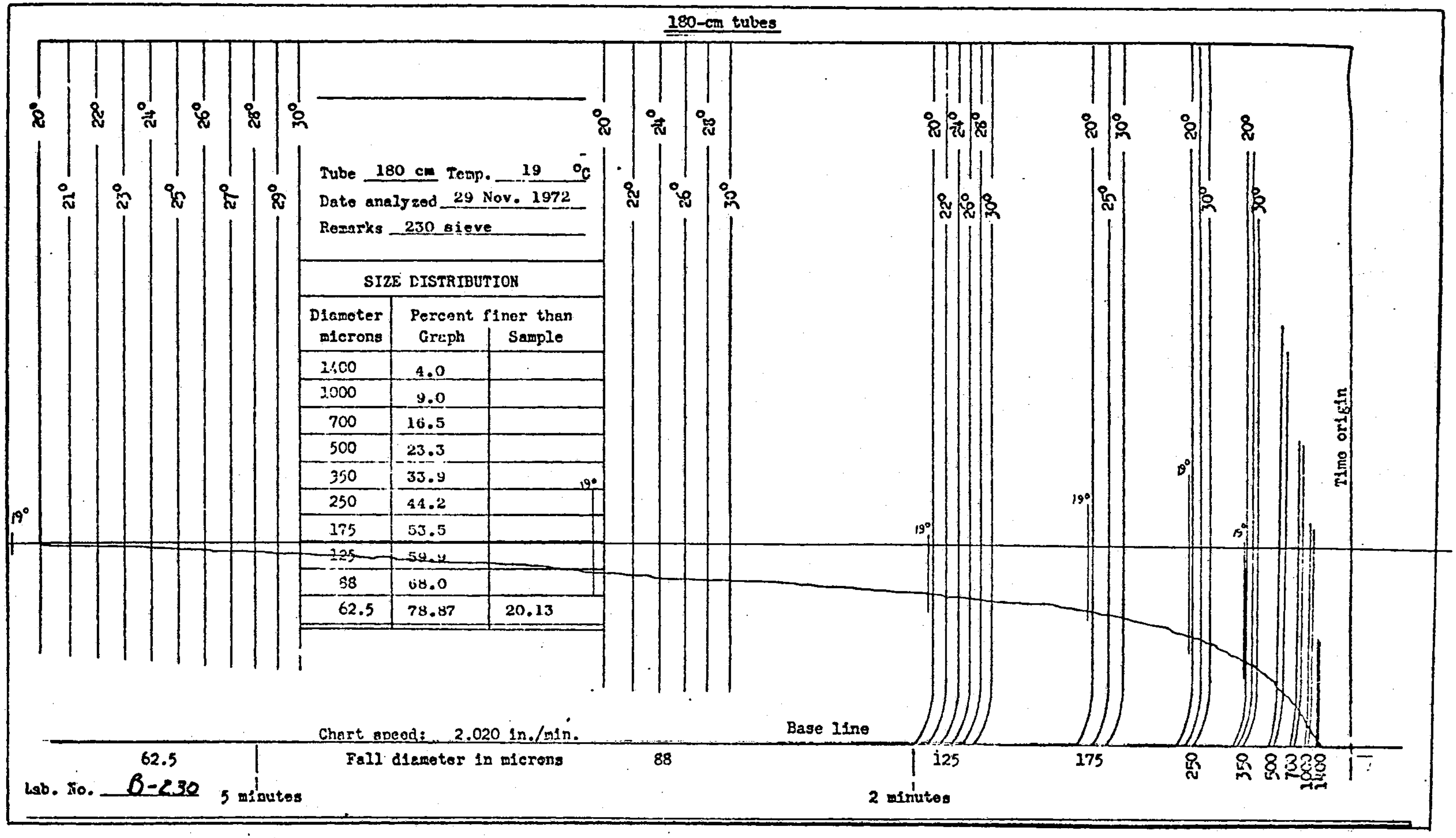
SIZE DISTRIBUTION

Diameter microns	Percent finer than Graph	Percent finer than Sample
1400		
1000	0.1	
700	1.1	
500	3.2	
350	17.5	
250	44.2	
175	73.0	
125	84.9	
88	91.0	
62.5	94.42	5.58

Chart speed: 2.020 in./min.

Lab. No. A-230

Figure 19. Visual Accumulation Tube Chart, Layer A



Tube 180 cm Temp. 19 °C

Date analyzed 29 Nov. 1972

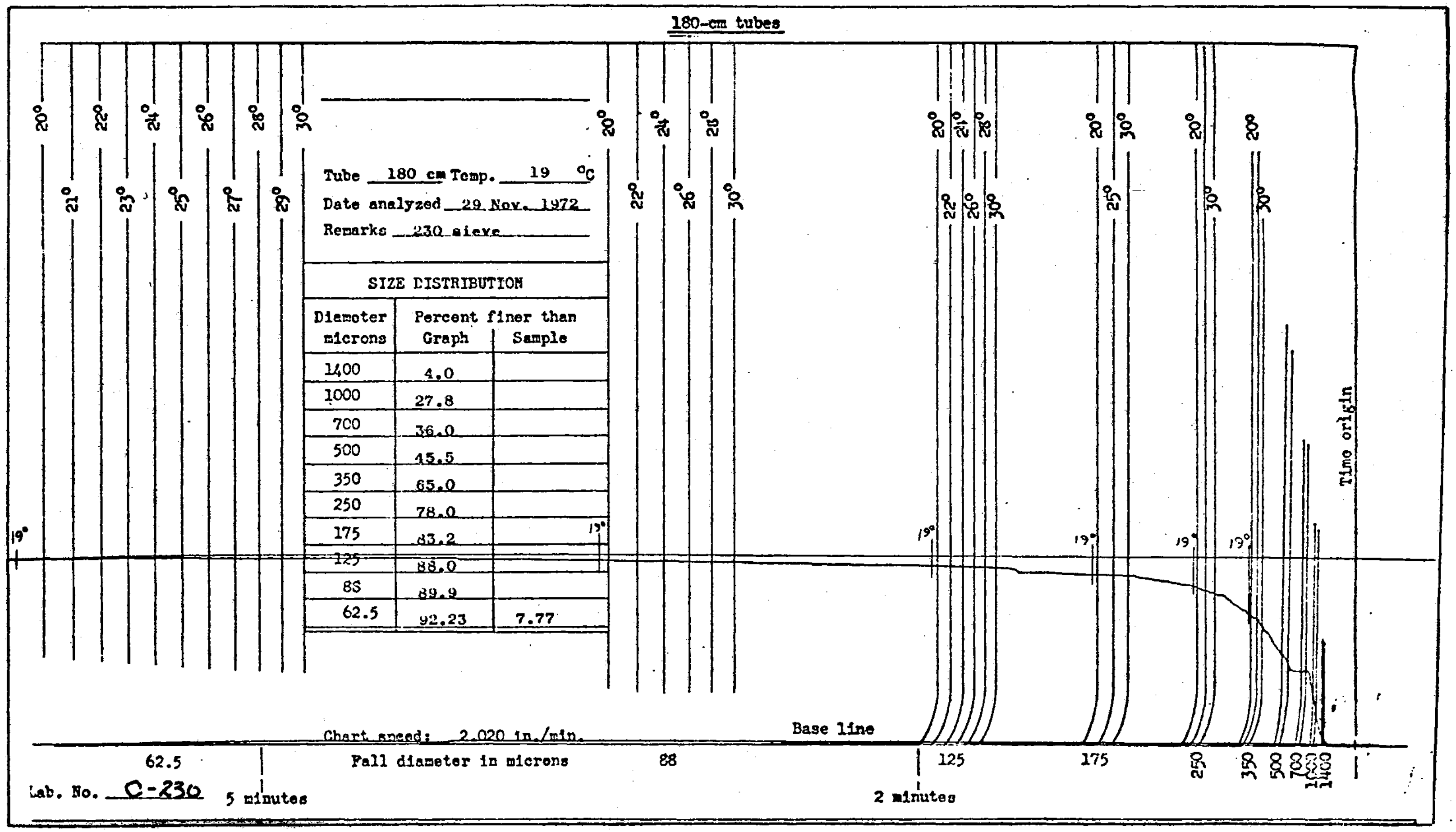
Remarks 230 sieve

SIZE DISTRIBUTION		
Diameter microns	Percent finer than	
	Graph	Sample
1400	4.0	
1000	9.0	
700	16.5	
500	23.3	
350	33.9	
250	44.2	
175	53.5	
125	59.9	
88	68.0	
62.5	78.87	20.13

Chart speed: 2.020 in./min.

Lab. No. B-230

Figure 20. Visual Accumulation Tube Chart, Layer B



Tube 180 cm Temp. 19 °C

Date analyzed 29 Nov. 1972

Remarks 230 sieve

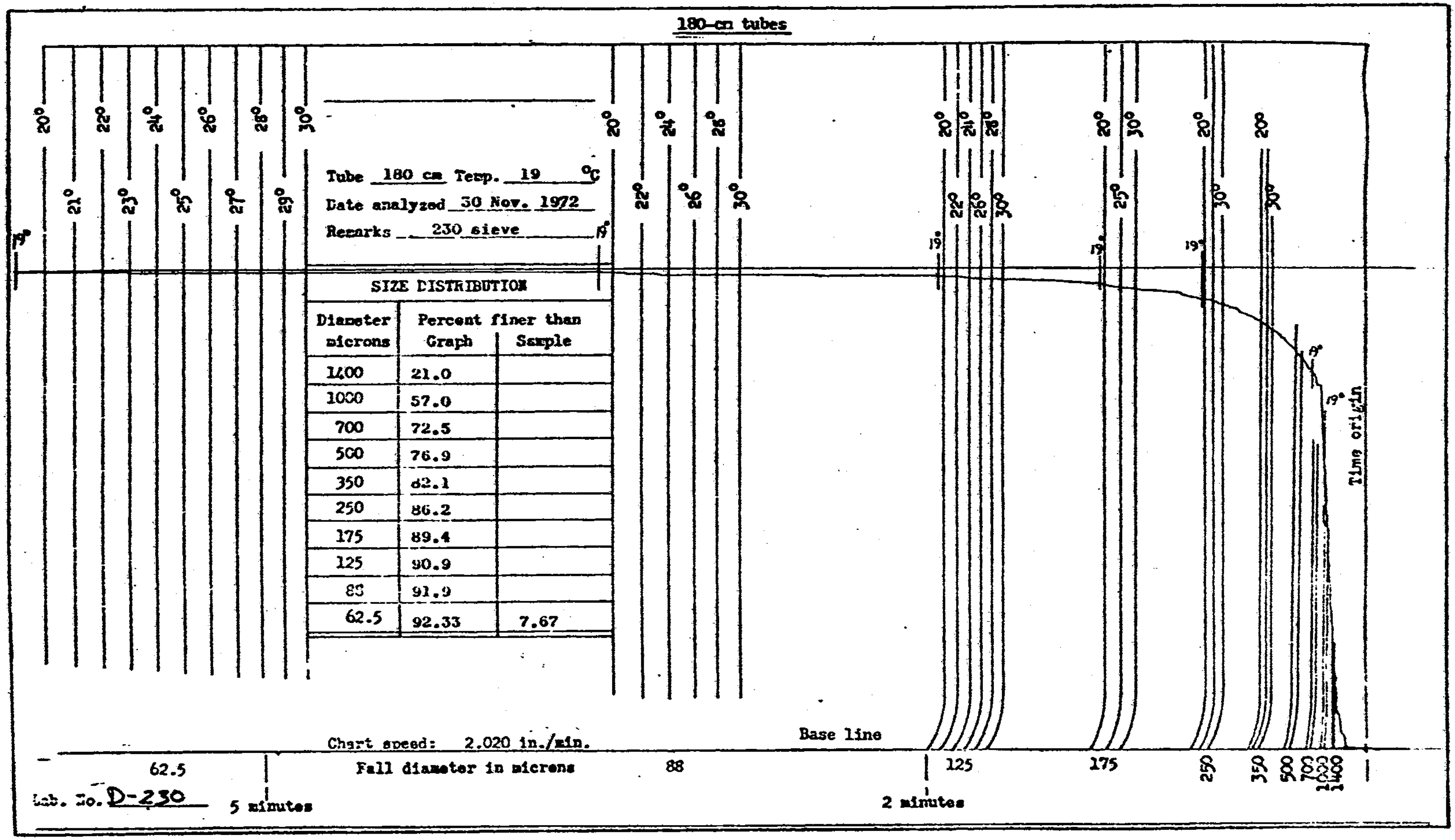
SIZE DISTRIBUTION

Diameter microns	Percent finer than Graph	Percent finer than Sample
1400	4.0	
1000	27.8	
700	36.0	
500	45.5	
350	65.0	
250	78.0	
175	83.2	
125	88.0	
88	89.9	
62.5	92.23	7.77

Chart speed: 2.020 in./min.

Lab. No. C-230

Figure 21. Visual Accumulation Tube Chart, Layer C



Tube 180 cm Temp. 19 °C

Date analyzed 30 Nov. 1972

Remarks 230 sieve

SIZE DISTRIBUTION

Diameter microns	Percent finer than Graph	Percent finer than Sample
1400	21.0	
1000	57.0	
700	72.5	
500	76.9	
350	82.1	
250	86.2	
175	89.4	
125	90.9	
88	91.9	
62.5	92.33	7.67

Chart speed: 2.020 in./min.

Lab. No. D-230

Figure 22. Visual Accumulation Tube Chart, Layer D

APPENDIX B

STORAGE PUMP TEST DATA

TABLE VI

STORAGE PUMP TEST, LAYERS A, B, C, D

t	s-o	s-a	Q
0.0	0.0	0.0	00.00
0.5	18.0	0.6	46.41
1.5	20.9	1.5	
2.0	21.8	2.2	58.29
2.5	23.7	2.8	
3.0	24.3	4.6	
3.5	25.1	4.9	
4.0	25.8	5.6	58.75
4.5	26.6	6.0	
5.0	27.1	6.6	
5.5	27.7	7.4	
6.0	28.6	8.1	59.07
6.5	29.4	9.8	
7.0	30.1	10.3	
7.5	31.0	10.4	
8.0	31.7	11.0	57.55
8.5	32.5	11.8	
9.0	33.3	12.4	
9.5	34.1	13.3	
10.0	34.8	14.1	58.24
10.5	35.8	14.6	
11.0	35.8	15.6	
11.5	37.4	16.3	
12.0	38.2	17.1	58.51
12.5	39.0	17.7	
13.0	39.8	18.4	
13.5	40.6	19.2	
14.0	41.3	20.0	59.22
14.5	42.2	20.7	
15.0	43.5	21.6	
15.5	43.7	22.3	
16.0	44.6	23.1	59.03
16.5	45.4	23.9	
17.0	46.3	24.6	
17.5	46.9	25.2	
18.0	47.7	26.0	59.42
18.5	48.6	26.8	
19.0	49.1	27.6	
19.5	49.9	28.3	

t = time,minutes
s-o = drawdown in obs. well, cm
s-a = drawdown in annulus, cm
Q = pump rate, ml/sec

TABLE VII

STORAGE PUMP TEST, LAYERS B, C, D

t	s-o	s-a	Q
0.0	0.0	0.0	00.00
0.5	18.9	0.4	48.89
1.0	21.1	1.1	
1.5	22.1	1.9	
2.0	23.0	2.6	57.09
2.5	23.8	3.4	
3.0	24.7	4.1	
3.5	25.5	4.9	
4.0	26.4	5.7	56.96
4.5	27.1	6.6	
5.0	28.1	7.2	
5.5	28.7	8.0	
6.0	29.5	8.6	56.41
6.5	30.4	9.4	
7.0	31.0	10.1	
7.5	32.0	11.0	
8.0	33.7	11.6	57.26
8.5	33.5	12.3	
9.0	34.5	13.1	
9.5	35.2	13.8	
10.0	36.1	14.7	57.00
10.5	37.1	15.3	
11.0	38.1	16.1	
11.5	39.1	16.7	
12.0	40.1	17.1	56.01
12.5	41.9	18.1	
13.0	42.1	18.9	
13.5	43.2	19.7	
14.0	44.5	20.3	56.02
14.5	45.9	21.1	
15.0	47.0	21.7	
15.5	48.2	22.4	
16.0	49.3	23.1	56.29
16.5	50.7	23.8	
17.0	52.0	24.5	
17.5	53.3	25.2	
18.0	54.8	25.8	56.65
19.0	58.0	27.3	
20.0	60.0	28.7	52.34
21.0	60.9	29.9	

t = time, minutes
s-o = drawdown in obs. well, cm
s-a = drawdown in annulus, cm
Q = pump rate, ml/sec

TABLE VIII

STORAGE PUMP TEST, LAYERS C, D

t	s-o	s-a	Q
0.0	0.0	0.0	00.00
1.0	30.2	1.0	50.86
2.0	33.1	2.2	48.78
3.0	33.8	3.5	
4.0	34.7	4.7	43.61
5.0	35.3	5.7	
6.0	35.7	6.7	38.61
7.0	36.2	7.6	
8.0	36.6	8.5	36.87
9.0	37.0	9.3	
10.0	37.3	10.1	34.75
11.0	37.6	10.9	
12.0	38.0	11.6	33.13
13.0	38.4	12.3	
14.0	38.7	12.9	30.81
15.0	39.0	13.6	
16.0	39.3	14.2	29.36
17.0	39.5	14.8	
18.0	39.8	15.4	27.84
19.0	40.0	15.9	
20.0	40.3	16.5	26.18
21.0	40.5	17.0	
22.0	40.7	17.6	25.03
23.0	40.9	18.0	
24.0	41.2	18.5	24.13
25.0	41.5	19.2	
26.0	41.6	19.4	23.01
27.0	41.8	19.9	
28.0	42.0	20.3	21.97
29.0	42.3	20.6	
30.0	42.4	21.1	21.08
31.0	42.6	21.6	
32.0	42.7	21.9	20.37
33.0	42.9	22.3	
34.0	43.0	22.6	
35.0	43.2	23.1	19.09
36.0	43.3	23.4	
37.0	43.5	23.8	
38.0	43.7	24.1	18.16
39.0	43.8	24.4	
40.0	43.9	24.7	
41.0	44.0	25.1	17.05
42.0	44.2	25.4	
43.0	44.3	25.7	
44.0	44.5	26.0	15.95
45.0	44.7	26.3	
46.0	44.8	26.5	
47.0	44.9	26.9	15.08
48.0	45.1	27.1	
49.0	45.2	27.4	
50.0	45.3	27.6	14.15
51.0	45.4	27.9	
52.0	45.6	28.1	
53.0	45.7	28.5	13.18
54.0	45.8	28.7	
55.0	46.0	29.0	
56.0	46.1	29.2	12.47
57.0	46.2	29.6	

t = time, minutes
s-o = drawdon in obs. well, cm
s-a = drawdown in annulus, cm
Q = pump rate, ml/sec

VITA

Jack Thomas Chowning

Candidate for the Degree of

Master of Science

Thesis: A MULTILAYER MODEL OF THE OGALLALA FORMATION IN OKLAHOMA

Major Field: Bioenvironmental Engineering

Biographical:

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